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NIST Tests of the Wireless Environment in Automobile Manufacturing Facilities

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Executive Summary

This report describes measurements carried out by members of the NIST Electromagnetics Division to study the wireless environment in automotive manufacturing facilities. Testing was performed at three facilities during 2006 and 2007. We studied an assembly plant, a very crowded environment having auto chassis bodies moving continuously along assembly lines; a metal stamping plant, consisting of large metal-working machinery housed in an older facility; and an engine plant, with a more modern open, assembly-line layout.

We conducted three types of tests in each plant: (1) A background ambient spectrum survey where the existing wireless environment in each facility was monitored over a 24-hour period, indicating the current level of radio activity over time at one location on the factory floor. (2) A spectral analysis of the 802.11b WLAN frequency band, providing a detailed view of the existing use of this common frequency band. (3) Reverberant cavity tests where the physical spacing between a source and receiver was varied to investigate the signal-scattering characteristics of the production floor. These last tests provided an indication of the level of direct versus reflected path propagation in the environment. Together, the three sets of tests provided enough information to characterize the propagation environment for many wireless technologies.

Background ambient tests of the wireless environment showed signals in expected frequency bands, including broadcast radio and television transmissions, cellular telephone transmissions, and transmissions carried out within the facilities. In the stamping plant, the background ambient tests also showed signals covering a broad range of lower frequencies, probably due to machine noise.

Our ultrawideband, synthetic-pulse measurements indicate that these manufacturing facilities are highly reflective, reverberant environments that can potentially complicate reliable performance of deployed wireless technology. Even under line-of-sight conditions, significant self-interference occurs when the transmitter and receiver are separated by only a few meters or more. When non-line-of-sight conditions occur, the transmission path becomes very noisy. However, spectrum analyzer tests conducted throughout the plant indicate that, for the current level of utilization of wireless technology, coverage can be maintained throughout the plants

when a sufficient number of transmitting and repeating nodes are used. However, if the use of wireless is to be expanded, interference may become a significant issue.

The measured results provide key parameters that describe the wireless propagation environment in representative manufacturing facilities. While measurement uncertainties are not reported, end users of these data are interested primarily in large-scale behavior on the order of tens of decibels. Including uncertainties on the order of ±1 dB is of little value when we are studying quantities that can vary by tens of decibels. Improved channel descriptions will be useful for assessing current and future deployment of wireless technology in heavy-industrial manufacturing environments, for standards development, and for qualifying wireless equipment for use in highly reflective environments such as those studied here. Work is currently underway at NIST to develop laboratory-based methods for qualifying the performance of wireless equipment for use in highly reflective environments such as those studied here.

1. Introduction

Wireless technology in a production environment offers the potential benefits of lower installation costs, increased flexibility, and reduced maintenance when compared to cabled systems. However, the highly reflective, dynamic environment in an automobile production facility can impede signal reception for wireless devices such as local-area networks (LANs), equipment-diagnostic tools, plant-floor controllers, and RFID tags and readers. This may hinder the automotive industry and other U.S. industrial sectors from taking full advantage of the increased efficiency, reliability, and economy of wireless networking. A first step to improving the implementation of wireless networks and control at automotive manufacturing facilities is to evaluate the propagation environment by carrying out precise measurements at appropriate frequencies.

Members of the NIST Electromagnetics Division conducted detailed studies of the wireless environment in three automotive manufacturing facilities: an assembly plant, an engine plant, and a metal stamping plant. Tests were conducted on August 4-6, 2006 and August 3-6, 2007. Three types of tests were carried out at each facility. First, we conducted a spectrum survey, where we monitored existing ambient signals in the environment over a 24-hour period. These "background ambient" measurements provide an indication of the current level of radio activity minute-by-minute at a representative location on the factory floor. The second set of tests measured the spectral activity at several locations throughout the facilities. These tests focused specifically on the 2.4 GHz industrial, scientific, and medical (ISM) unlicensed frequency band. Automotive plant wireless system engineers have expressed interest in additional utilization of systems in this band for telemetry and control on the production floor.

The third set of tests studied the scattering characteristics of the factory environment by use of a test source and receiver. The response of the environment to a pulse-like signal was measured, giving an indication of the level of direct versus reflected path propagation in the environment, as summarized in a metric called the RMS delay spread. This information can be useful in engineering additional wireless system deployments and determining the required level of immunity to interference for

new equipment. After an overview of the test set-up, the procedure and results for each test are discussed below.

2. Test Set-up

2.1 The physical environment

The industrial environments represented by these manufacturing plants contain metallic structures and objects that can have a profound effect on radio reception. Transmitted radio signals reflect off objects before arriving at the radio receiver, and in so doing they can create interference. The size, shape, and materials of the factory environment will impact radio reception. An understanding of the physical environment can help to explain the measurement results and will enable development of appropriate lab-based tests to replicate these environments.

The first set of tests was carried out in an assembly plant whose dimensions are approximately 500 m x 250 m (1600 ft x 750 ft). The building is about 15 m (45 ft) high and constructed out of metal. The receiving site ("R" on Figure 2-1 below) for the background ambient tests, at Test Point "x", was about 70 m (210 ft) from the left end of the building near columns "S7" and "S8". The column indicators are noted on the left and upper side of the figure. For the scattering tests, a cart carrying the transmit antenna moved down aisle "S" approximately 300 m (1000 ft) from the receiving location.

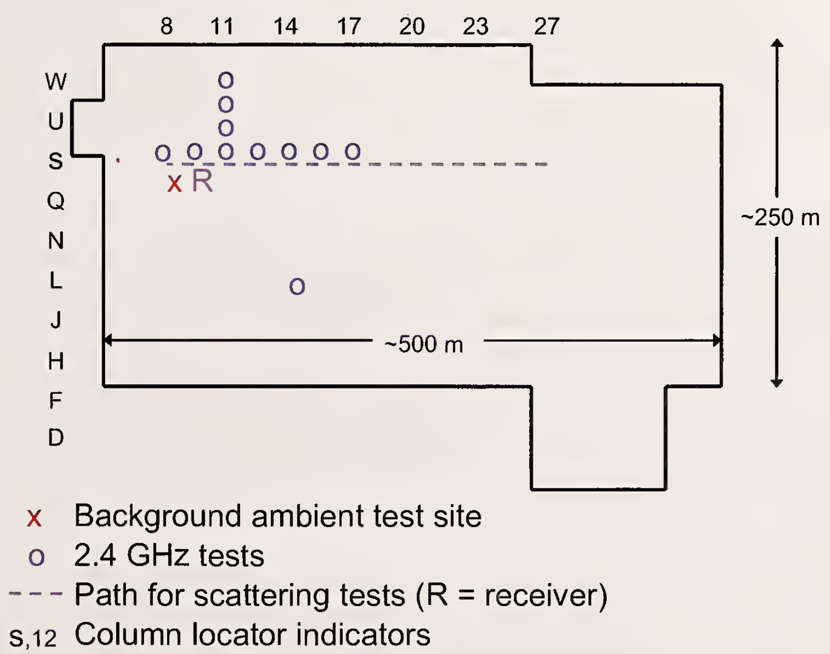


Figure 2-1: Rough outline of assembly plant where NIST wireless testing was carried out. The plant contains numerous assembly lines, catwalks, and other metallic objects and structures. The location of NIST receiving equipment for the background ambient tests is marked by an x. The dashed line indicates the path taken during the reverberant cavity tests. The locations of the 2.4 GHz spectrum analyzer tests are marked with circles.

The second set of tests was carried out in a metal stamping plant, referred to as the stamping plant in what follows. This facility contains large metal-working machinery, along with racks of parts, assembly lines, and offices. About half of the building dates to the 1940s, and the other half was added in the 1990s. The building is divided into large sections, as shown below in Figure 2. The dimensions of the building are approximately 850 m x 760 m (2800 ft x 2500 ft). The building was about 15 m (45 ft) high. The newer portion is constructed of metal with a concrete floor and the older section is a mix of cinderblock, metal, and windows with floors of either concrete or wood. Our tests were conducted in different areas of the building: The receivers for our background ambient tests were set up at location "x" in Figure 2-2; a cart carrying the transmit antenna moved along the path denoted by a dashed line for the scattering tests; and the 2.4 GHz spectrum analyzer tests were conducted throughout the facility at locations marked with circles.

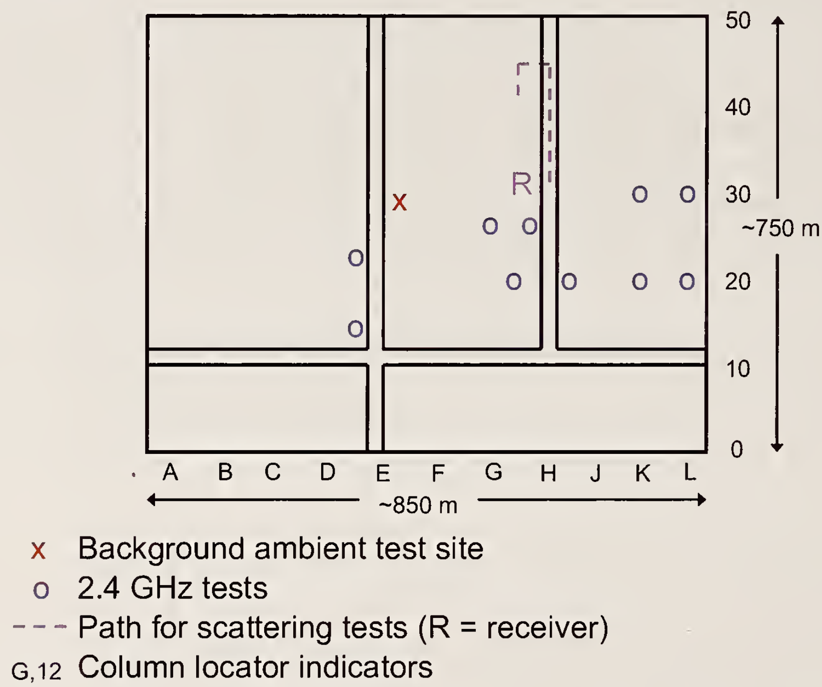


Figure 2-2: Rough layout of the stamping plant where NIST wireless testing was carried out. The plant contained assembly lines, heavy machinery, parts racks, and other metallic objects and structures.

The third building was an engine assembly facility, referred to as the engine plant in what follows. This facility has a more open layout than the stamping plant or the assembly plant, with low-profile assembly-lines throughout the building. This is a very new facility, constructed in 2000. Its dimensions are approximately 215 m x 305 m (700 ft x 1000 ft). The ceilings were approximately 15 m high and made of metal. Again, we carried out each set of tests in various parts of the facility. The receivers for the background ambient tests were conducted at the location marked with an "x" on Figure 2-3; the cart with the transmit antenna for the scattering tests moved along the path

marked with a pink dashed line; and the 2.4 GHz spectrum analyzer tests were conducted throughout the facility at locations marked with circles.

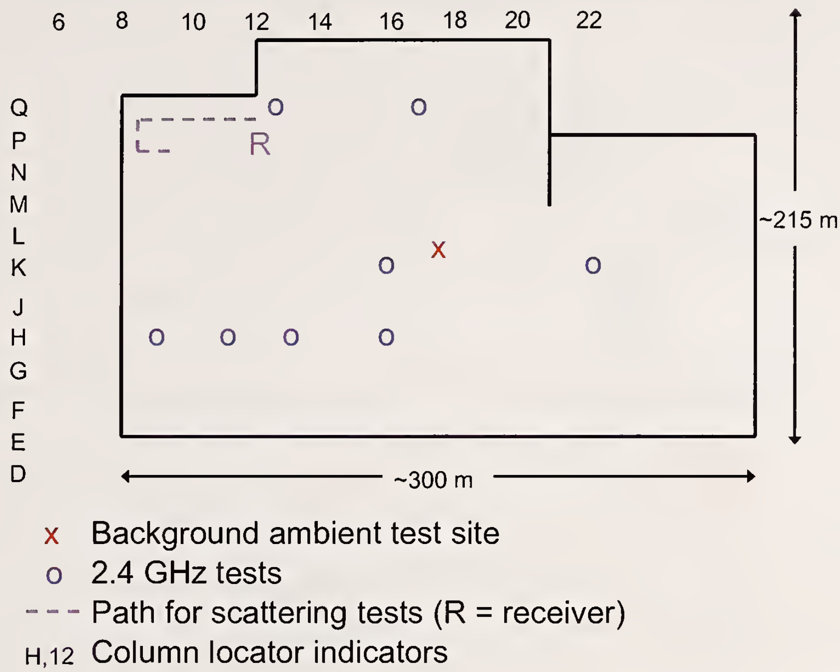


Figure 2-3: Layout of the engine plant where NIST wireless testing was carried out. The plant was more open than the assembly and stamping plants, although there were numerous assembly lines, parts racks, mobile fork trucks, and other metallic objects and structures.

This facility is relatively open. Large machinery is located throughout the structure, but most machines were spaced several meters apart, connected by assembly lines. A number of metallic objects and surfaces are located throughout the facility including testing machinery, metal platforms, fences, beams, and conveyors, as well as mobile forklifts and maintenance vehicles.

The stamping plant and the engine plant are much more open than the assembly plant we tested in 2006. Both have wide aisles and areas containing racks of parts. Because both plants had certain areas that were more crowded with machines, we carried out a number of the 2.4 GHz tests in these areas to study radio coverage and interference.

We would expect that large metal buildings like these with expansive metal surfaces and a very complex maze of reflective machinery would cause radio signals to scatter erratically or reverberate throughout the structure. These various signals travel in multiple complicated paths from transmitter to receiver. These multiple signal paths, known simply as 'multipath', typically involve different distances depending on how signals of a given frequency reflect off the metal surfaces. The concept of multipath is illustrated in Figure 2-4. When multiply reflected signals arrive at the receiver, they arrive at slightly different times. They may either add or subtract from the direct path signal, causing constructive or destructive interference, respectively. When the

interference becomes severe, radio communication may be lost. When the reflecting surfaces are in motion the received signal strength is even more variable. A good understanding of the relationship of these multipath signals to the direct (desired) signal is important in developing wireless systems that would work reliably in this environment.

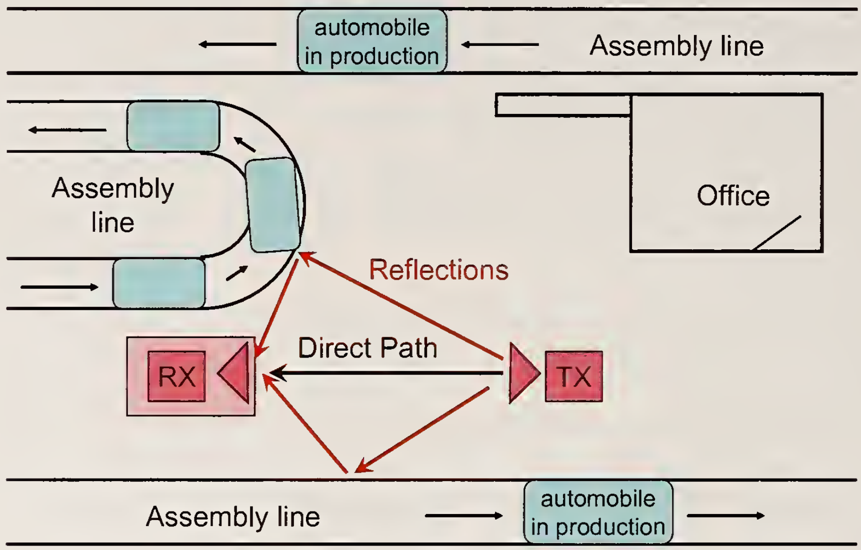


Figure 2-4: Multiple reflections (multipath) occur when signals propagating between the transmitter and receiver reflect off metallic objects or structures. The different paths cause the signals to arrive at the receiver at slightly different times.

2.2 The wireless propagation environment

As described above, the physical environment in all three facilities was quite reflective. This means that even weak radio signals from transmitters located a distance away could be received and could potentially interfere with desired radio signals. Knowledge of what radio technologies are deployed on the production floor can help interpret the measured results.

One primary use of radio technology in these facilities is for broadband data transfer by use of a wireless local-area network (WLAN). These plants use the IEEE 802.11b^{TM} or 802.11a^{TM} standards [1-3]. The 802.11b standard consists of eleven channels operating on frequencies between 2.4 GHz and 2.472 GHz. These are considered "wideband" systems, since each channel spans about 20 MHz of spectrum to provide rapid data transfer. In comparison, a "narrowband" system may occupy only a few kilohertz to approximately a megahertz of spectrum. For all three plants studied, the WLAN transceivers (or nodes) were tuned to channels 1, 6, and 11. This is standard practice for minimizing interference between nodes. The nodes used in these facilities are mounted high overhead to provide the best line-of-sight radio connection between nodes. The 2.4 GHz "Industrial, Scientific, and Medical" (ISM) frequency band is unlicensed, which means other applications such as cordless phones, handheld

wireless games, as well as industrial control and telemetry equipment, can operate in this band.

Other wireless systems commonly used in industrial facilities include handheld radios for point-to-point communications. These radios are often used by maintenance and operational personnel for voice communications. These operate in the 900 MHz ISM frequency band. Cellular telephones used by staff operate at frequencies around 850 MHz and 1.9 GHz. Cordless phones and other consumer electronics operating in the 5.2–5.9 GHz ISM unlicensed frequency band may also be used. At lower frequencies, radio interference from heavy equipment ("machine noise") can impact signals. The tests below let us study these frequency bands to determine the level of interference between different systems in a particular band.

3. Background Ambient Spectrum Analyzer Tests

3.1 Measurement set-up

Reception of desired wireless signals can be affected by users in a given frequency band as well as by out-of-band signals. Background ambient tests help to provide an understanding of the current wireless environment in a given facility, including potential in-band and out-of-band interference. This knowledge can be used to help mitigate existing interference issues, as well as to help ensure that future deployment will not face insurmountable interference.

Figure 3-1 describes the measurement system used in our tests. A spectrum analyzer captured the ambient signals emitted by wireless devices, broadcast stations, and from unintentional emitters such as motors in machines. We were interested primarily in frequencies below 6 GHz, since these are the frequencies currently used for unlicensed voice and data wireless transmission. We recorded signals from a fixed location over 24-hour periods. For our first set of measurements in the assembly plant, we recorded signals over two 24-hour periods. We found little difference between data from one day to the next. Consequently, we recorded signals over one 24-hour period in the stamping and engine plants.

In each plant, we used three spectrum analyzers: one for the lower frequencies (20 MHz to 1.3 GHz), one for mid-range frequencies (1 GHz to 6 GHz), and a third to monitor the higher frequencies (6 to 18 GHz). For the highest-frequency set-up, we were aware that the combined broad frequency band and low antenna sensitivity would result in a high noise floor. As a result, these measurements can identify only high-level signals in this band.

In the assembly plant tests, we used omnidirectional antennas for all three frequency bands. In the stamping plant and the engine plant, we used omnidirectional antennas in the lowest and highest frequency bands and directional antennas for the middle band. In all cases, measurement data were collected continuously over the length of the test. This extended period for data collection tells us whether wireless traffic changes throughout the day; for example from production times to non-production times. The test site in each plant is indicated by the red "x" in Figures 2-1 through 2-3. Figure 3-2 shows a layout of the test equipment in the assembly plant, and Figures 3-2

and 3-3 show photographs of the measurement set-ups in the stamping and engine plants.

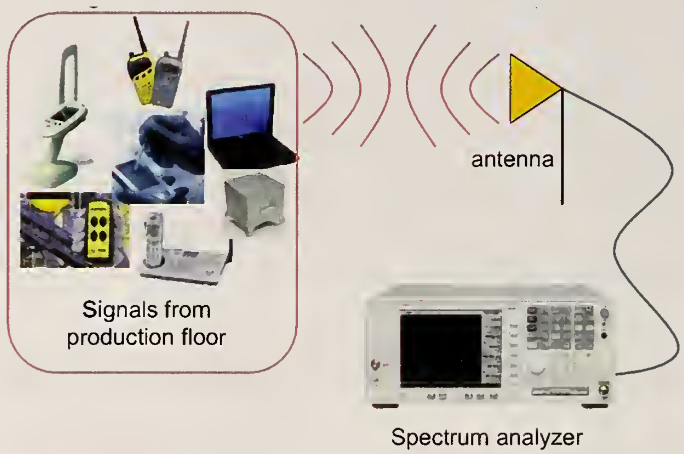


Figure 3-1: Background ambient tests use a spectrum analyzer to measure signals from all types of wireless devices, from broadcast stations, and from unintentional emitters such as large machines over a long period of time.

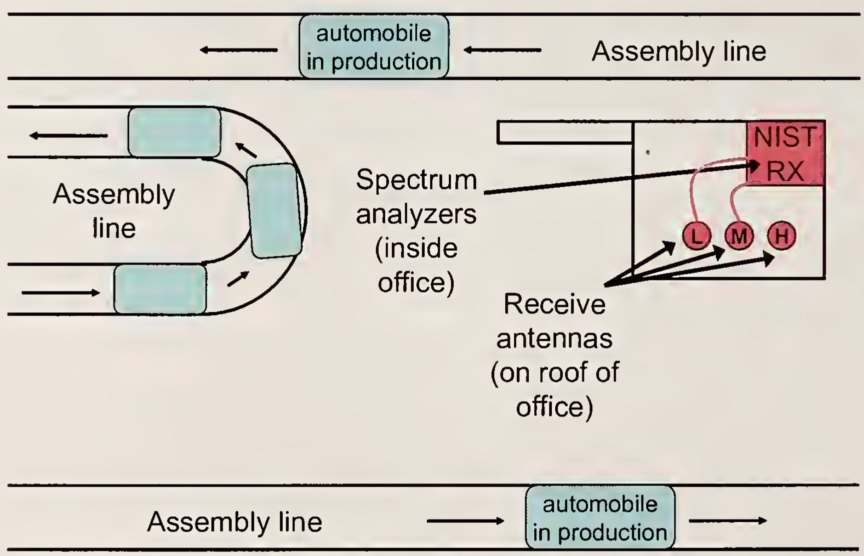
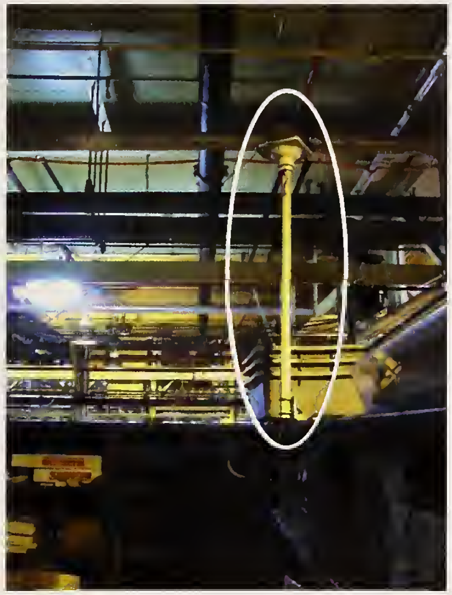


Figure 3-2: Antenna and receiver locations for background ambient tests at the assembly plant. As shown in Figure 2-1, the office where the receivers were located was on aisle "S."

(a)



(b)

(c)

Figure 3-3: Background ambient tests carried out at the stamping plant. (a) A mid-frequency-range directional antenna located on a second-story-office roof is shown by the right-hand circle. A low-frequency, omnidirectional antenna was mounted between platforms, and is shown by the left-hand circle. (b) An omnidirectional antenna used for the high-frequency band was mounted on the platform to the left of the directional antenna in (a). (c) The second-story office where the three spectrum analyzers were located.

(a)

(b)

(c)

Figure 3-4: Background ambient tests carried out at the engine plant. The antennas and measurement system were located on a catwalk approximately 15 m above the plant floor. (a) A mid-frequency-range directional antenna. (b) A low-frequency, omnidirectional antenna was mounted on the catwalk hanging down over the production floor. (c) The three spectrum analyzers were located on the catwalk as well.

The spectrum analyzers were programmed to acquire approximately 100 data sweeps every minute, and each sweep consisted of 8192 frequencies. Every 100 sweeps, a computer program calculated the average and maximum at each frequency and saved these data files. Thus, we have a representation of the average and maximum every minute throughout one (approximately) 24-hour period. The recording

times are listed in Table 3-1 below. At the stamping plant, the different start and stop times occurred due to technical issues. The operational schedules for these facilities during these times are shown in Table 3-2.

Table 3-1: Start and stop times for the background ambient tests.

Assembly Plant Run #2 (2006)

Frequency band	Start: Friday August 4	Stop: Saturday August 5
Low	8:30 a.m.	7:15 a.m.
Mid	8:30 a.m.	7:15 a.m.
High	8:30 a.m.	7:15 a.m.

Stamping Plant (2007)

Frequency band	Start: Friday August 3	Stop: Saturday August 4
Low	1:25 p.m.	12:08 p.m.
Mid	1:26 p.m.	12:09 p.m.
High	10:36 a.m.	8:21 p.m. (August 3)

Engine Plant (2007)

Frequency band	Start: Sunday August 5	Stop: Monday August 6
Low	1:45 p.m.	1:05 p.m.
Mid	1:45 p.m.	2:34 p.m.
High	1:47 p.m.	2:49 p.m.

Table 3-2: Production schedules during the background ambient tests.
Left side: assembly and engine plants. Right side: stamping plant.

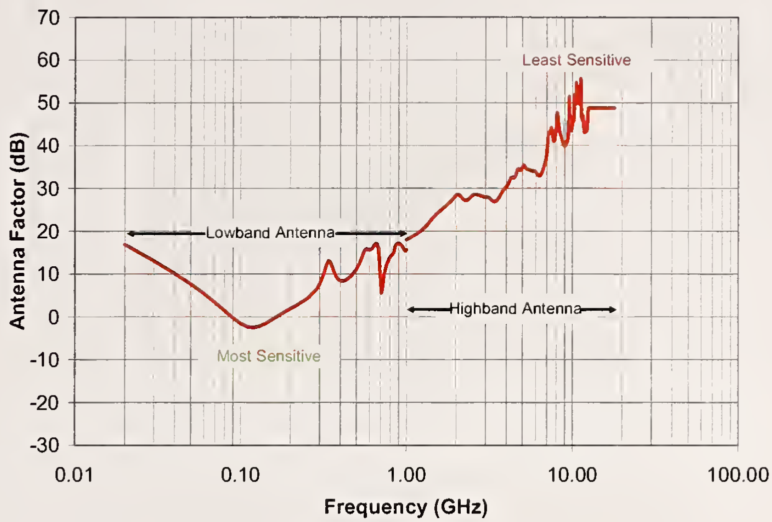
Assembly Plant	
Aug 3 – 5, 2006	
Day Shift	
Start:	6:00 a.m.
Break:	9:30 - 9:45 a.m.
Lunch:	11:00 - 11:30 p.m.
Break:	1:00 - 1:15 p.m.
Shift End:	2:30 p.m.
Afternoon Shift	
Start:	3:30 p.m.
Break:	5:30 - 5:45 p.m.
Lunch:	9:00 - 9:30 p.m.
Break:	10:45 - 11:00 p.m.
Shift End:	12:00 a.m.
Engine Plant	
Aug 5 – 7, 2007	
Shift Start:	6:00 a.m.
Break:	9:00 - 9:15 a.m.
Lunch:	11:00 - 11:45 a.m.
Break:	1:30 - 1:52 p.m.
Shift End:	4:30 p.m.

Stamping Plant	
Aug 3, 2007	
1st shift	
Shift Start:	7:00 a.m.
Break:	9:00 - 9:16 a.m.
Lunch #1:	11:30 AM - 12:00 p.m.
Lunch #2:	11:45 AM - 12:15 p.m.
Cleanup:	2:55 - 3:00 p.m.
Aug 3, 2007	
2nd shift	
Shift Start:	3:00 p.m.
Break:	5:00 - 5:16 p.m.
Lunch:	7:30 - 8:00 p.m.
Cleanup:	10:55 - 11:00 p.m.
Aug 3-4, 2007	
3rd shift	
Shift Start:	11:00 p.m.
Break:	1:00 - 1:16 p.m.
Lunch:	3:30 - 4:00 p.m.
Cleanup	6:55 - 7:00 p.m.
Aug 4, 2007	
1st shift	
Shift Start:	7:00 AM
Break:	9:00 - 9:16 a.m.
Lunch #1:	11:30 - 12:00 a.m.
Lunch #2:	11:45 a.m.- 12:15 p.m.
Cleanup:	2:55 - 3:00 p.m.

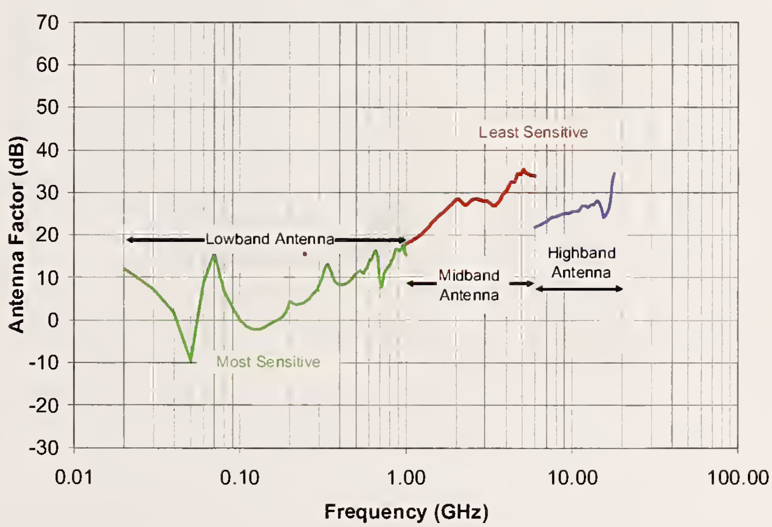
The background ambient data presented below have been corrected for the antenna characteristics and represent the actual electric field strength (in dB relative to 1 v/m) incident on the antenna. The antenna factors used are shown in Figure 3-5. The antenna factor represents the transfer function of the antenna from incident field strength to terminal voltage. We apply the antenna factor to the measured power recorded by the spectrum analyzer to determine the electric field strength picked up by the antenna. The antenna factors for these antennas were determined from direct measurements using the two-identical antenna method on the NIST open-area test site.

In practice, the antenna factor is valid for a particular aspect angle and will vary depending on the directional gain of the antenna. The antenna factors for the omnidirectional antennas are strictly valid only in the horizontal plane (zero-degree elevation angle) and, depending on the arrival angle of the radio wave, could be several decibels in error. Fortunately, the directional gain of these antennas is such that the zero-degree elevation angle antenna factor appears to be a reasonable average value over all the aspect angles. Notice in Figure 3-5 that the antenna factors are quite large at the higher frequencies, which makes it difficult to detect weak signals. The noise floor

of the spectrum analyzer is relatively constant with frequency; so the minimum signal we can measure is determined essentially by the antenna factor curve.



(a)



(b)

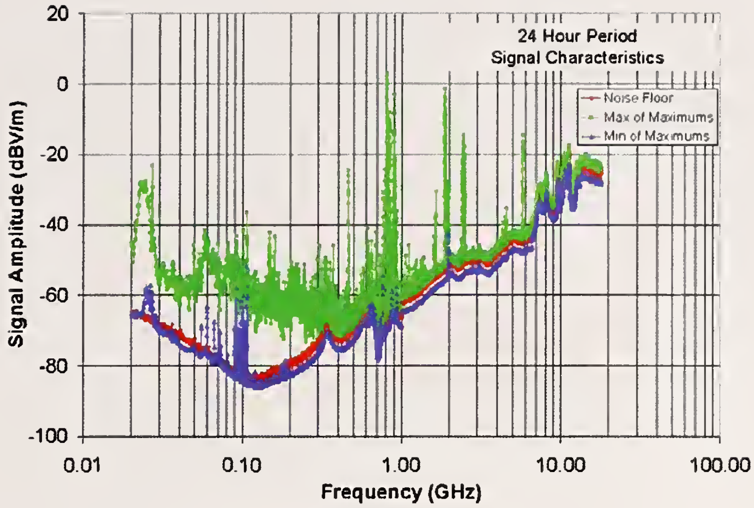
Figure 3-5: Antenna factors for the receiving antennas used in the (a) assembly plant and (b) stamping and engine plants. In the assembly plant, we used the same antenna type for the mid- and high-band measurements.

Note that throughout this work, measurement uncertainties are not reported. End users of these data are primarily interested in large-scale statistical behavior on the order of tens of decibels. Including uncertainties on the order of 1 dB is of little value when we are studying quantities that can vary by tens of decibels.

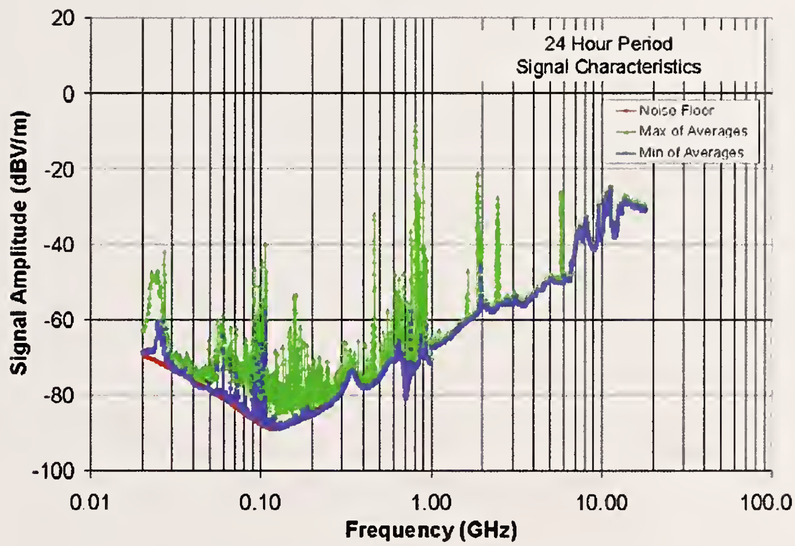
3.2 Signal ranges over 24 hours

To summarize the large amount of data collected, we processed the recorded data. Each data file contained the average or maximum received signal at each frequency over a one-minute interval, and stored over the duration of the entire measurement (approximately 24 hours). Thus, at each frequency, we collected a set of over 1200 time samples. We then took the minimum and maximum of those time samples to obtain an overall minimum and maximum at each frequency. This leads to some admittedly confusing terminology when we refer to the maximum of the maxima, the maximum of the averages, or the minimum of the maxima.

Figures 3-6 and 3-7 show the extreme values of the (a) maximum and (b) average field measured over the entire spectrum from 20 MHz to 18 GHz for all three sites. As expected, no strong signals were detected above 6 GHz. However, the noise floor of the instruments increases significantly with frequency.

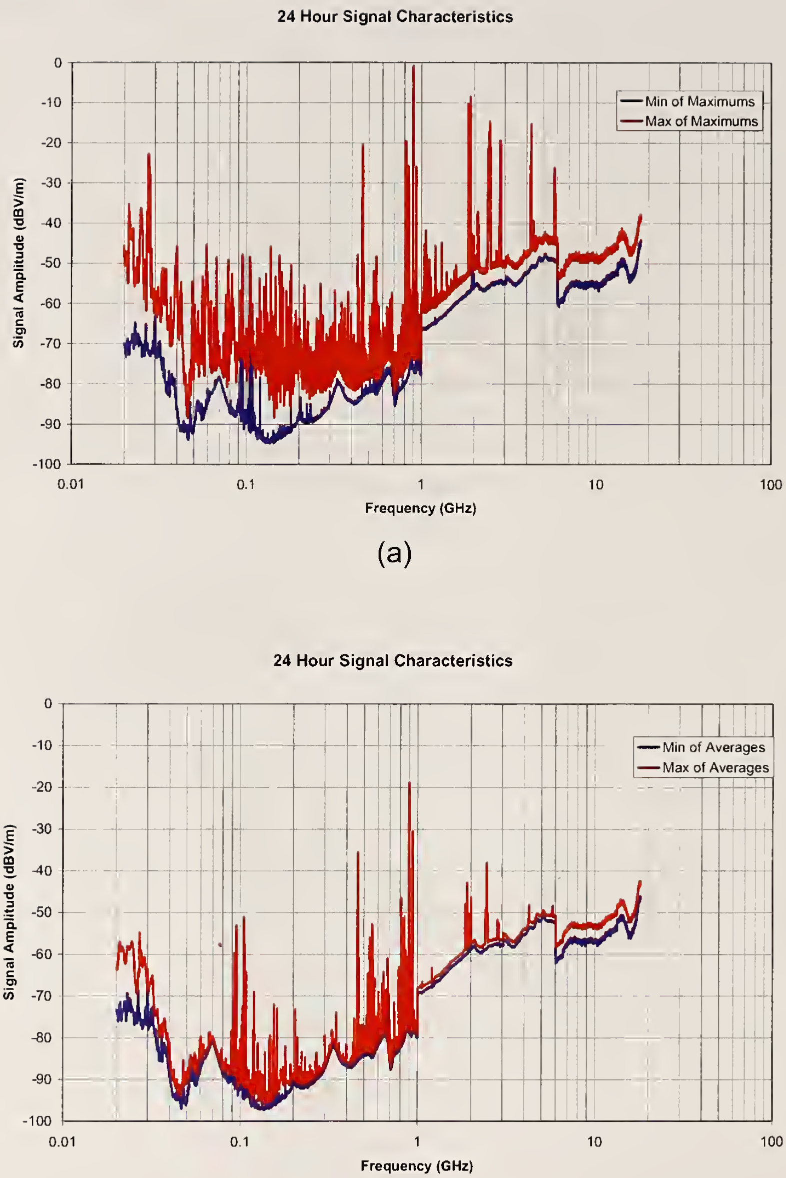


(a)



(b)

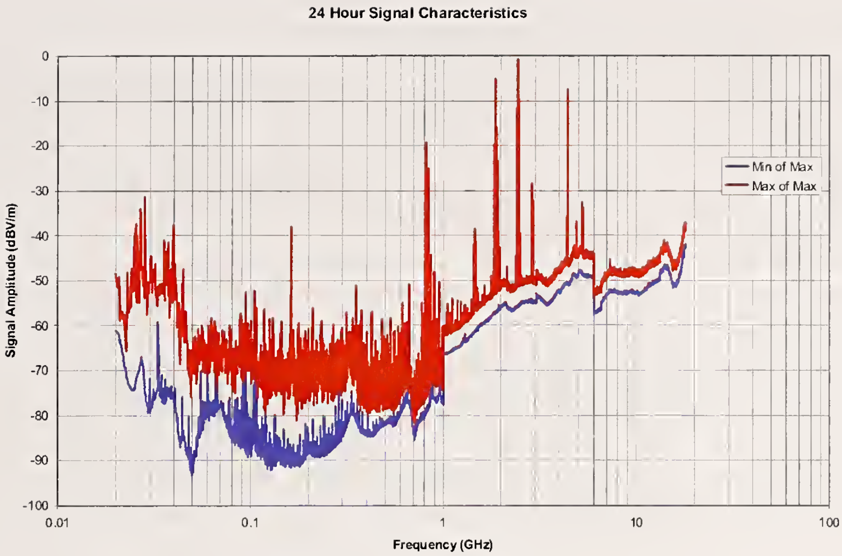
Figure 3-6: 24-hour signal amplitudes at the assembly plant. In (a), we computed the maximum of all recorded data collected during each minute, and then computed the minimum (dark blue curve) or maximum (light green curve) of each value over the 24-hour period. In (b), we computed the average of all recorded data collected during each minute, and then computed the minimum (dark blue) or maximum (green) of each value over the 24-hour period. In each graph, the noise floor is plotted in red.



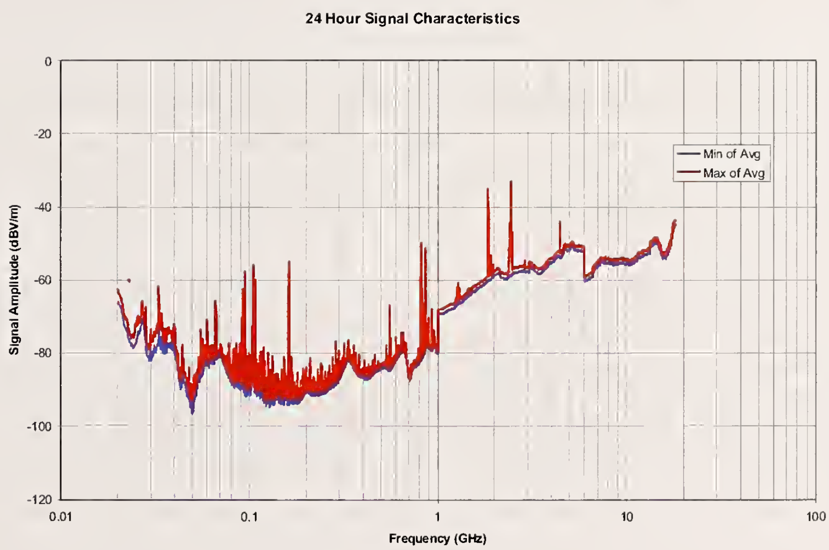
(a)

(b)

Figure 3-7: 24-hour signal amplitudes at the stamping plant. In (a), we computed the maximum of all recorded data collected during each minute, and then computed the minimum (dark blue curve) or maximum (light red curve) of each value over the 24-hour period. In (b), we computed the average of all recorded data collected during each minute, and then computed the minimum (dark blue) or maximum (red) of each value over the 24-hour period.



(a)



(b)

Figure 3-8: 24-hour signal amplitudes at the engine plant. In (a), we computed the maximum of all recorded data collected during each minute, and then computed the minimum (dark blue curve) or maximum (light red curve) of each value over the 24-hour period. In (b), we computed the average of all recorded data collected during each minute, and then computed the minimum (dark blue) or maximum (red) of each value over the 24-hour period.

3.3 Ambient signals in key frequency bands

The data collected for this evaluation of the wireless environment represent a comprehensive evaluation of the electromagnetic environment at a specific location within each plant. We briefly summarize some of our relevant findings for devices employed in production facilities such as these. We also discuss our methods for processing and presenting the results.

We begin by examining two of the frequencies in and near the FM broadcast band. These two frequencies are representative of the typical signal characteristics throughout the measured spectrum. Figure 3-9 shows the measured field over time at 106.7 MHz (an active FM radio channel) and at 109.0 MHz (slightly above the FM band with no apparent communication activity). The amplitude of the 106.7 MHz signal is roughly stable between −55 dBv/m and −40 dBv/m. The red curve represents the maximum observed signal over 100 samples, and the blue curve represents the average observed signal. The offset between these two curves is roughly constant at around 4 dB.

Surprisingly, we see that the variation of the 106.7 MHz signal with time correlates well to the general operation of the plant, with lower levels observed while the assembly line was shut down. At 109.0 MHz, the readings are essentially at the noise floor of our instrumentation, with occasional spikes thrown in. Again the maximum observed signal is approximately 4 dB higher than the average, although the spikes show a much larger difference (as large as 20 dB). This indicates that the spikes are rare events, occurring only once or twice out of 100 samples. Since little information appears to be lost by examining the maximum observed signal, but using the average tends to diminish the effect of the spikes, we will focus on the maximum observed signal for the remainder of our analysis.

Presenting data similar to those shown in Figure 3-9 is not a tractable option for the more than 24,000 frequencies that we measured. Instead, we took a time series at several key measurement frequencies, similar to those shown in Figure 3-9, and computed five statistics: the minimum, the 25th percentile or lower quartile, the median, the 75th percentile or upper quartile, and the maximum. Together, these five statistics are referred to as a “five-number summary” of a set of data. Such a summary obviously loses information such as when a transition occurs or the duration of any transition, but does indicate how often an interfering signal might be present. For the 106.7 MHz and 109.0 MHz signals, the minimum, lower quartile, median, and upper quartile are tightly grouped (approximately 5 dB variation) but the maximum is significantly higher (sometimes over 20 dB higher) than the upper quartile, indicating that high-amplitude signals are rare. Communication around a frequency that shows very little activity is possible as long as error correcting/detecting methods are used to recover from the occasional noise spike.

Figure 3-10 shows the five-number summaries for frequencies in the FM broadcast band. For each channel, the characteristics are similar to those of the 106.7 MHz channel. Between channels, the characteristics are similar to those shown at 109.0 MHz.

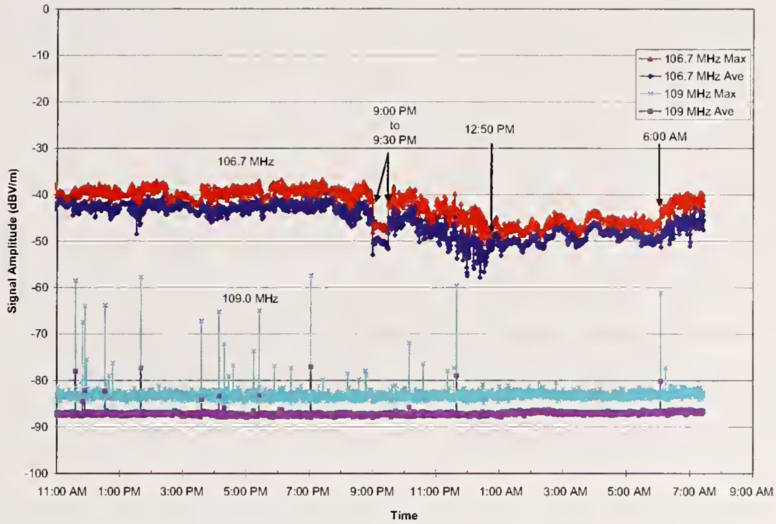


Figure 3-9: Maximum and average ambient signals at 106.7 MHz and 109 MHz from the assembly plant measured over a 24-hour period August 3-4, 2006.

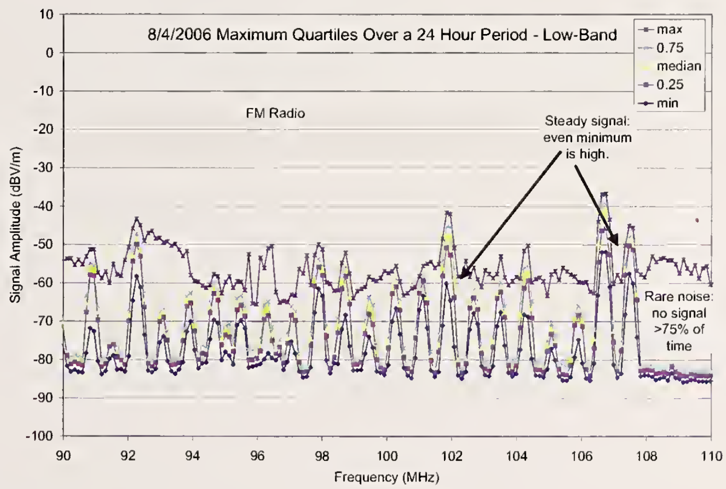
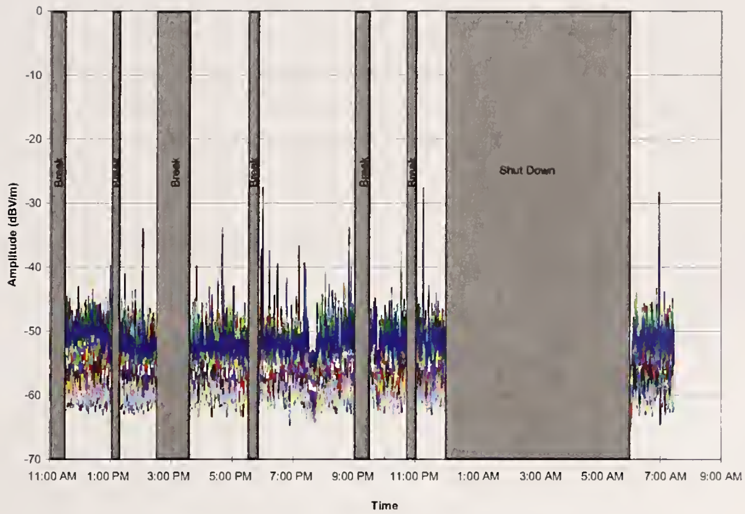


Figure 3-10: Ambient signals represented by a five-number summary in the FM broadcast band between 90 MHz and 110 MHz measured in the assembly plant and collected over a 24-hour period, August 3-4, 2006.

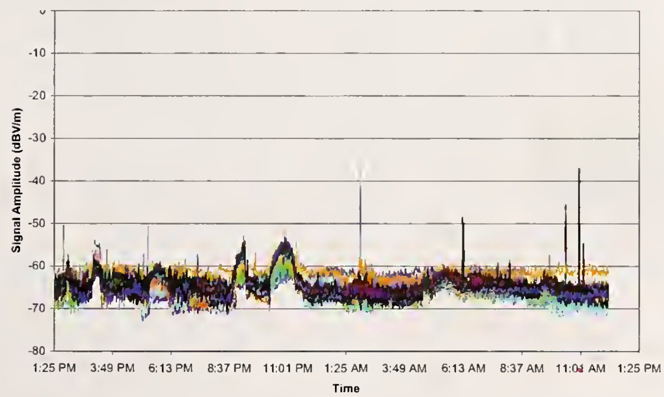
If several frequencies in a band have similar characteristics, we can overlay the traces to illustrate the commonalities. For example, Figures 3-11(a) through (c) show an overlap of all 43 frequencies measured between 20 MHz and 25 MHz at the three facilities. In 3-11(a), we see good correlation between the activity in the assembly plant and the level of electromagnetic emissions. The curves from the stamping and engine plants in 3-11(b) and (c) show three different characteristics: periods of low activity, periods of extended high activity, and short spikes of very high activity, possibly due to someone passing by the receiver site or a spike in the power or activity on the production floor. The broadband nature of the extended characteristics, along with the timing of the low-activity periods, indicates that the observed signals may be related to machinery that are energized during certain times of plant operation and either turned off or not operated during breaks. For example, the time window between 11 p.m. and 5:30 a.m. in the stamping plant indicates that certain machinery may not be used during the third shift.

We next examine some of the frequency bands of interest to wireless communication engineers. Figures 3-12(a), (c), and (e) show a three-dimensional representation of the signals around 5.8 GHz for the three facilities. We plot amplitude versus both frequency and relative time (number of minutes after the start of the measurement). Figures 3-12(b), (d), and (g) show the five-number summaries over the same frequency band for the three plants.

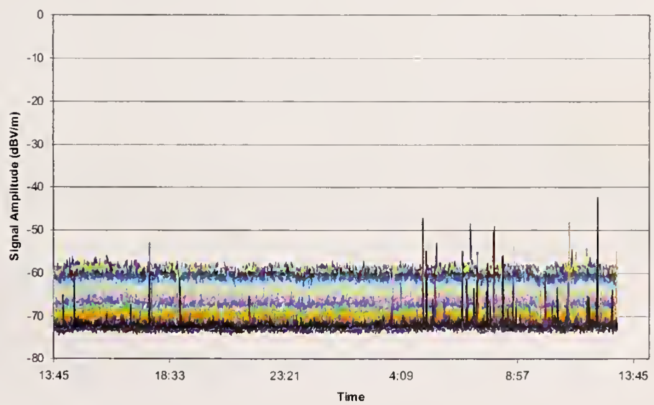
In the assembly plant and the stamping plant, we see bursts of signal activity in this frequency band. Activity in the stamping plant occurs regularly, less so in the assembly plant. The signals cover a broad frequency range, but occur infrequently during the 24-hour period. Both types of graphs support this conclusion. For the engine plant, we see that the 5.8 GHz frequency band is not currently in use.



(a)



(b)



(c)

Figure 3-11: An overlay of the 43 measured frequencies between 20 MHz and 25 MHz collected during a 24-hour period at (a) the assembly plant, August 3-4, 2006, (b) the stamping plant, August 3-4, 2007 and (c) the engine plant, August 5-6, 2007.

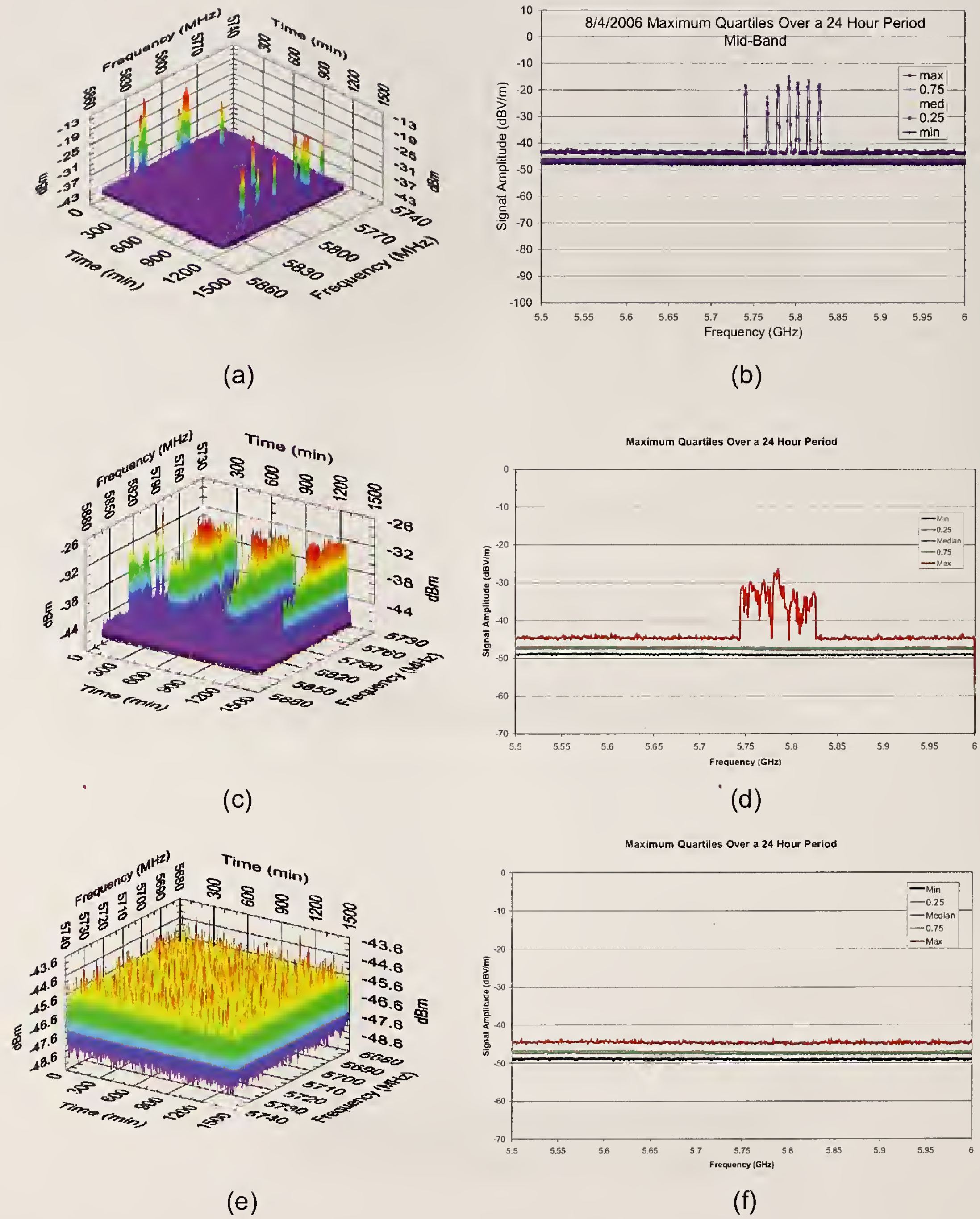


Figure 3-12: Received signal levels at 5.8 GHz collected over a 24-hour period. **Left column:** Signal level versus frequency (right axis) and time (left axis) for the (a) assembly plant, (b) stamping plant, and (e) engine plant. **Right column:** A five-number summary of the same data for (b) assembly plant, (d) stamping plant, and (f) engine plant.

The frequency band from 902 MHz to 928 MHz is often used for handheld wireless communication in industrial plants, while cell phone communications may be found in the 800 MHz frequency range. Figures 3-13(a)-(f) show radio activity in these bands. In the assembly plant, we see a great deal of activity in the 900 MHz band arising from plant floor communications. However, both the stamping plant and engine plant show little activity, with intermittent activity in the 800 MHz cellular band.

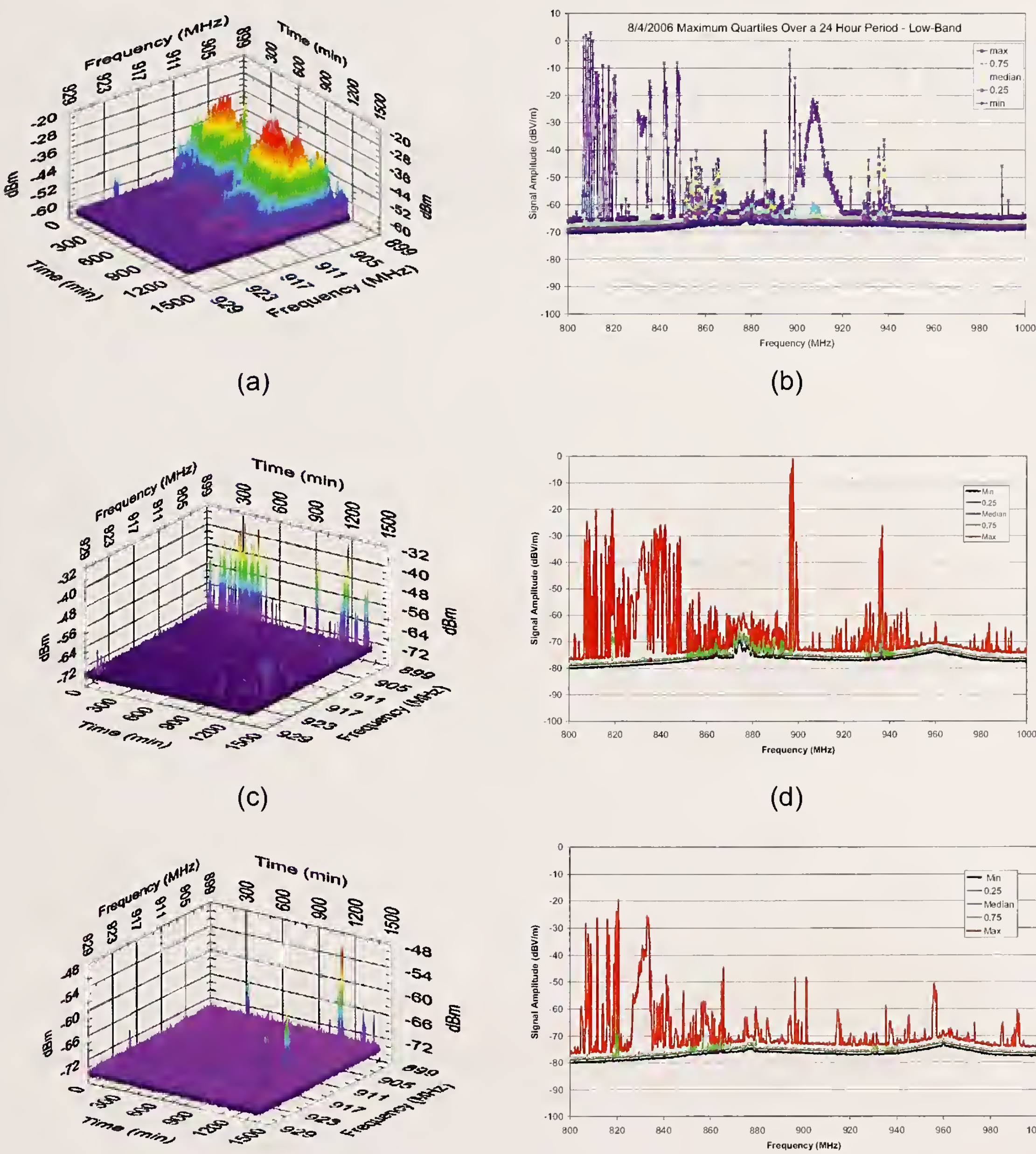


Figure 3-13: Received signal levels at 900 MHz collected over a 24-hour period. **Left column:** Signal level versus frequency (right axis) and time (left axis) for the (a) assembly plant, (b) stamping plant, and (e) engine plant. **Right column:** A five-number summary of the same data for (b) assembly plant, (d) stamping plant, and (f) engine plant.

The spectrum usage around 2.4 GHz is shown in Figure 3-14. In Figure 3-14(a) and (c), the 3-D representation shows high-level signals at certain frequencies. For the engine plant, Figure 3-13(e), we see consistent, low-level use of the 2.4 GHz band across the entire band (Figure 3-14(c)). The median in Figure 3-14(f) clearly shows one of the WLAN channels being used. The remainder of the usage is probably due to some other type of transmission system involving a frequency-hopping transmitter.

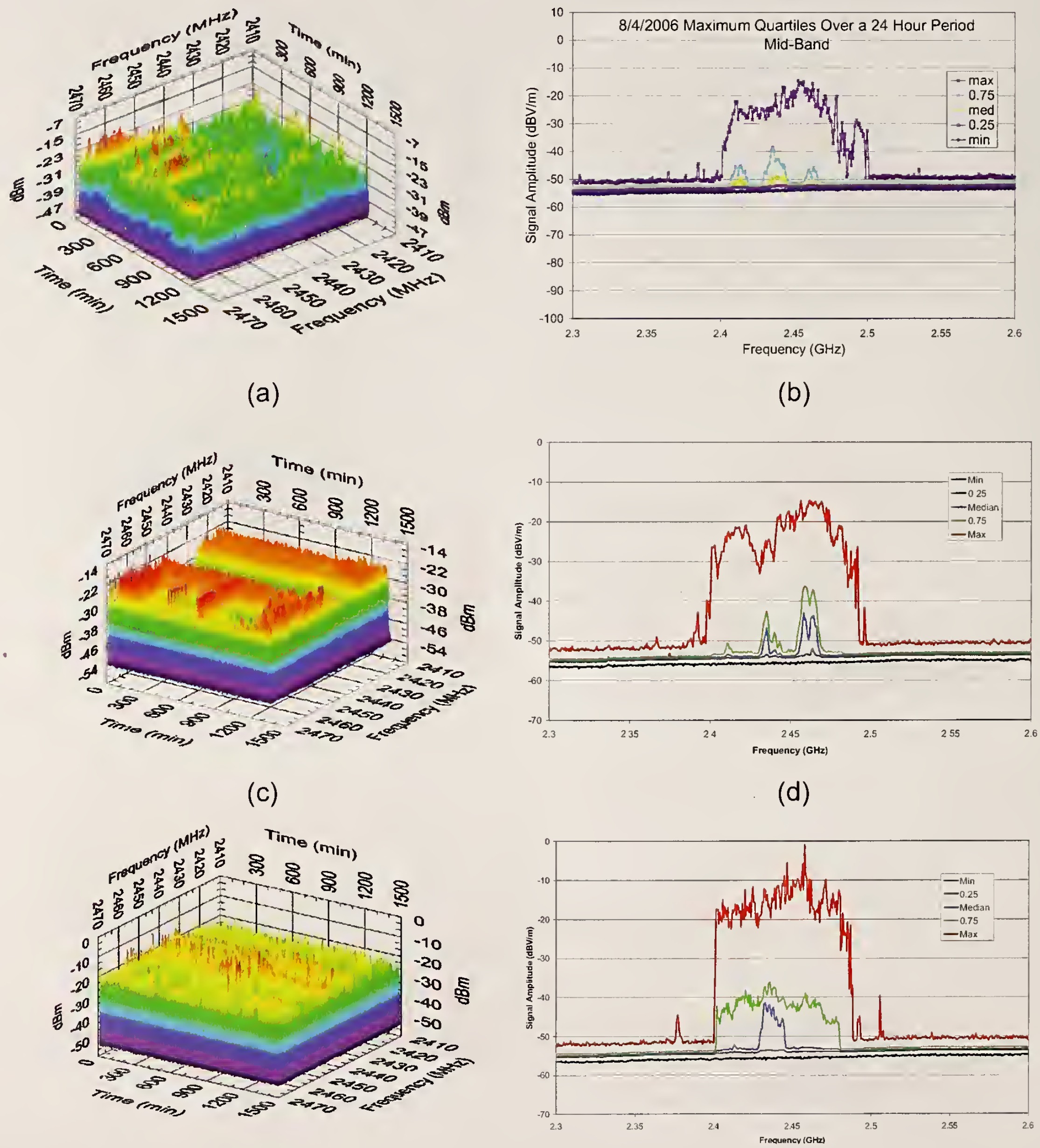
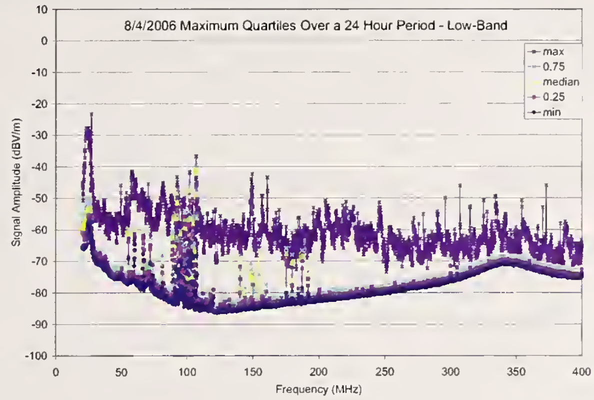
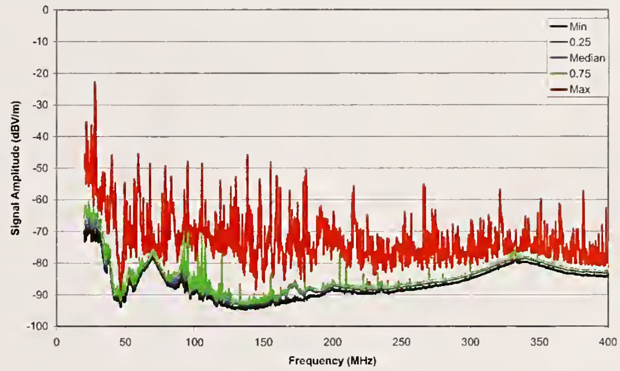


Figure 3-14: Received signal levels at 2.4 GHz collected over a 24-hour period. **Left column**: Signal level versus frequency (right axis) and time (left axis) for the (a) assembly plant, (b) stamping plant, and (e) engine plant. **Right column**: A five-number summary of the same data for (b) assembly plant, (d) stamping plant, and (f) engine plant.

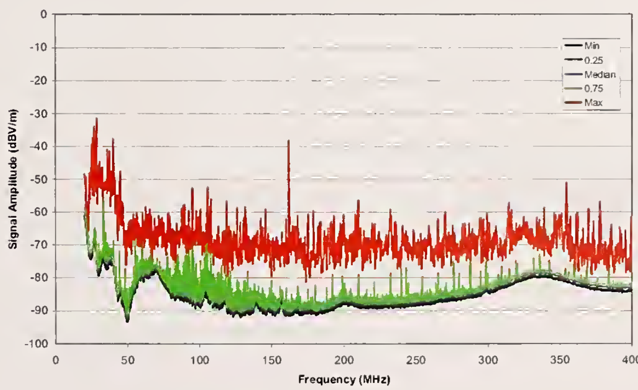
Figure 3-15 shows low-frequency ambient signals from 10 MHz to 400 MHz. Below 400 MHz, the entire spectrum appears to be filled with noise, with a few obvious communication signals. For the stamping plant, there are several higher-level, intermittent signals at the lower frequencies. Much of this noise is probably related to the older, heavy machinery used in plant operations.



(a)



(b)



(c)

Figure 3-15: Low-frequency data (10–400 MHz) from (a) the assembly plant, (b) the stamping plant, and (b) the engine plant. Data were collected over a 24-hour period.

At 1.9 GHz, see Figure 3-16, (probable cell phone traffic) we see characteristics common to all plants. Below 1.95 GHz, the signals are less consistent, with high maxima, but low levels for the other statistics. These are likely transmissions from nearby individual cell phones. The lower-level signals are probably from a base station.

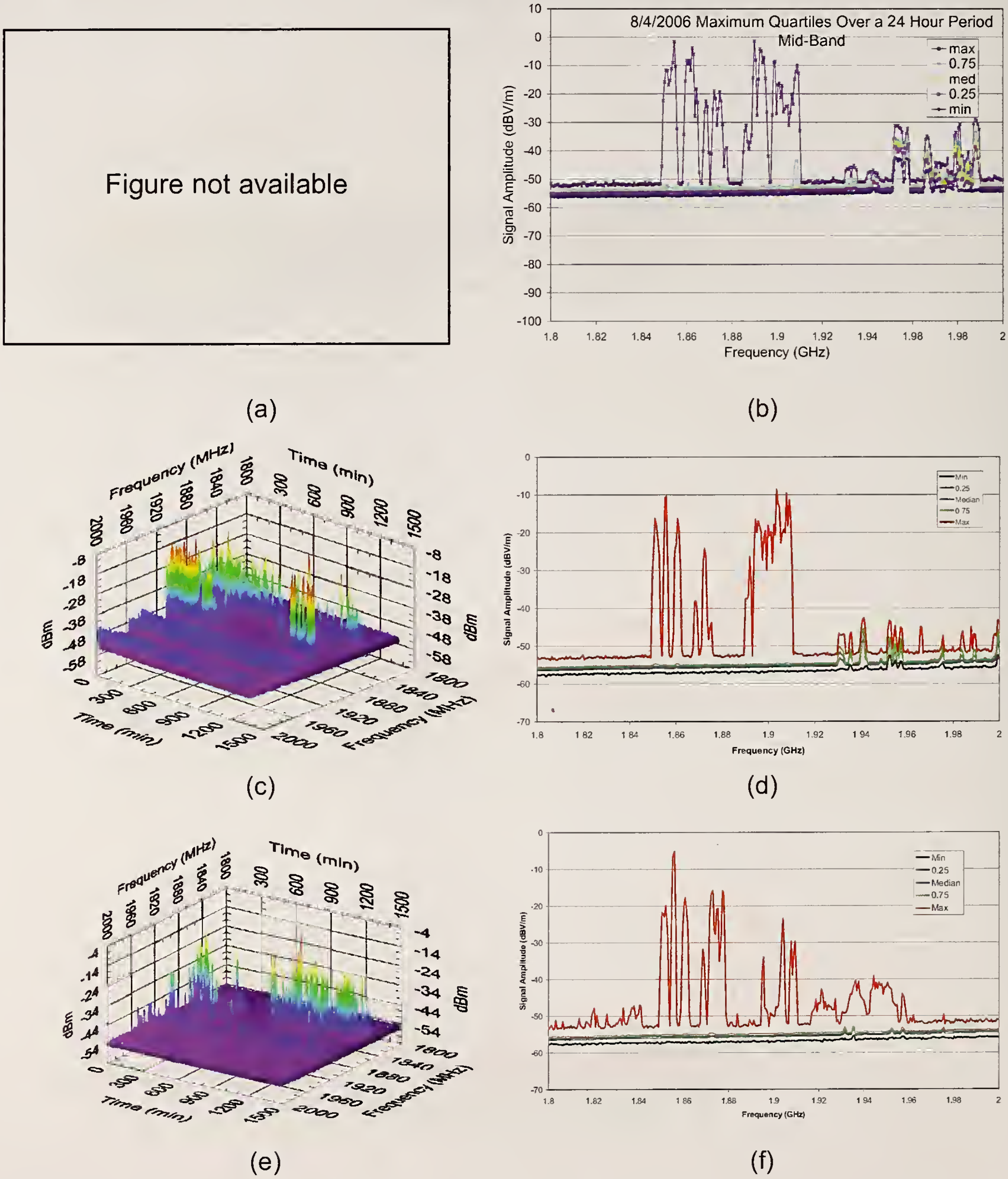


Figure 3-16: Received signal levels at 1.9 GHz collected over a 24-hour period. **Left column:** Signal level versus frequency (right axis) and time (left axis) for the (a) assembly plant (not available), (b) stamping plant, and (e) engine plant. **Right column:** A five-number summary of the same data for (b) assembly plant, (d) stamping plant, and (f) engine plant

The background ambient results presented here show wireless activity in expected frequency bands. The levels of activity seem very well defined. Broadcast stations can be received within the older stamping plant building, primarily because of the number of windows in this facility. Machine noise seems to be a significant issue in the stamping plant, but not the engine plant, at the locations studied. The 5.8 GHz band gets intermittent-to-little use. This may change as more wireless technology is deployed at these frequencies. We studied the 2.4 GHz band in more detail below.

4. Spectrum Analyzer Measurements of the 2.4 GHz Frequency Band

Many types of wireless equipment utilize the 2.400 GHz – 2.484 GHz unlicensed frequency band, including WLAN systems used for data transfer, specialized equipment on the factory floor, and personal electronics, such as wireless handheld games or cordless phones. All of these different uses can lead to radio interference that can impair or even disable critical manufacturing equipment. Use of additional transceiver nodes to overcome interference or to fill in "dead spots" can actually create additional interference, especially in highly reflective environments, and must be positioned carefully. To provide additional insight into current use in this common frequency band on the production floor, we collected spectrum analyzer "snapshots" at locations throughout all three plants in the frequency range between 2.4 GHz and 2.5 GHz, as illustrated in Figure 4-1.

For these measurements, we used a portable spectrum analyzer connected to an omnidirectional antenna. Figure 4-2 shows the type of set-up used, although in practice we used a half-wave dipole antenna mounted on a metallic base for measurements above 1 GHz. The spectrum analyzer and antenna were carried throughout the plants and signals were recorded at the locations shown in Figures 2-1 through 2-3. Measurements were repeated at most locations on two different days. The goal of these tests was first to evaluate the coverage of existing transmissions throughout the plant, and second to determine whether there are any significant interfering sources in the present environment.

Measurements were carried out with the "peak hold" feature of the spectrum analyzer turned on. This indicated the overall level of signal received at a particular location over the period for which the peak hold was engaged. Note that the signal levels presented in the measurement data give only relative values since we did not correct the measurements for the antenna used.

Note that throughout this work, measurement uncertainties are not reported. End users of this data are primarily interested in large-scale statistical behavior on the order of tens of decibels, thus including uncertainties on the order of 1 dB is of little value.

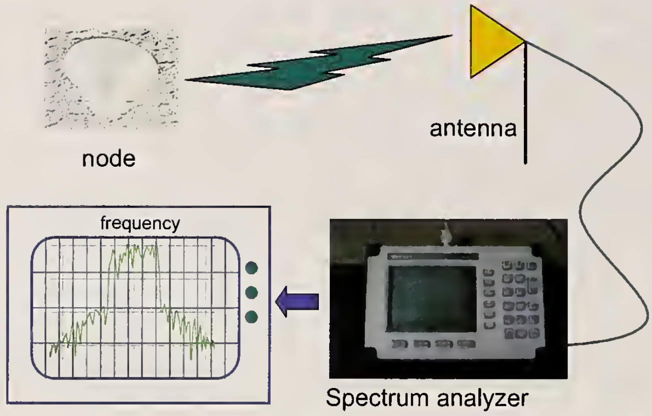


Figure 4-1: Measurement set-up for the handheld spectrum analyzer tests.

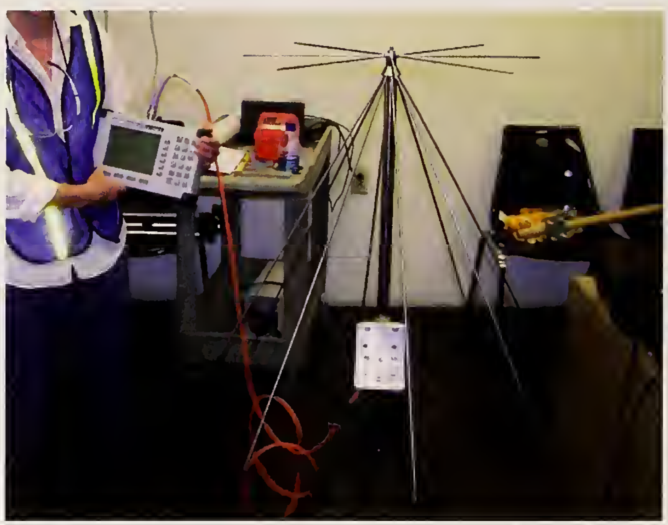


Figure 4-2: Photograph of the portable spectrum analyzer and omnidirectional antenna used to collect snapshots of spectrum throughout the three plants. The antennas shown here were used at frequencies up to 1 GHz. Other omnidirectional antennas were used at higher frequencies.

We first show results from a series of measurements along aisle "S" in the assembly plant (see Figure 2-1). Using the handheld spectrum analyzer and a small rubber-coated helical monopole (rubber duck) antenna, we moved from column "S7" to column "S17", about 170 m (500 ft.) away. Figure 4-3 shows the results of this set of measurements. While the 802.11b WLAN signals are very weak at S17, they can be detected almost continuously from S7 to that location. Midway, around S11, we see the transition from one node operating on channel 6 at 2.437 GHz to another node, operating on channel 11 at 2.462 GHz. Coverage is quite good down the aisle.

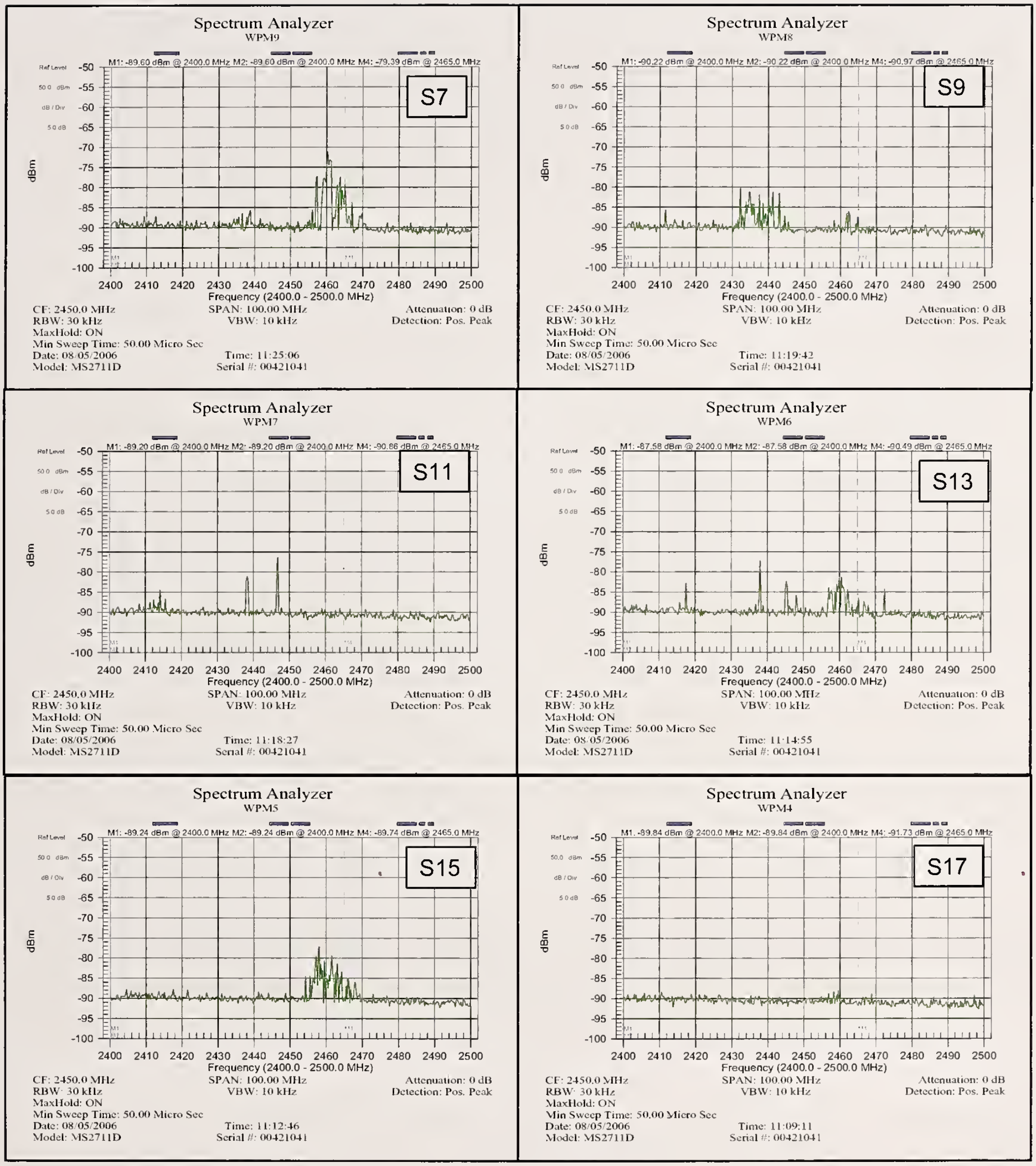


Figure 4-3: Handheld spectrum analyzer measurements made while moving approximately 150 m (500 ft) down aisle S. Note that the center frequency of the 802.11b WLAN signal changes between S9 and S11, indicating reception from another node.

Figure 4-4 shows results of measurements at various locations in the stamping plant during production. Each graph was collected over a one-minute period on August 3, 2007 using the "peak hold" function on the spectrum analyzer. We see that 802.11b signals are being transmitted on channels 1, 6, and 11 (center frequencies of 2.412 GHz, 2.437 GHz, and 2.462 GHz). These signals were received at every location we tested, although in some cases the reception was quite weak, for example, channel 1 in Figure 4-4(c).

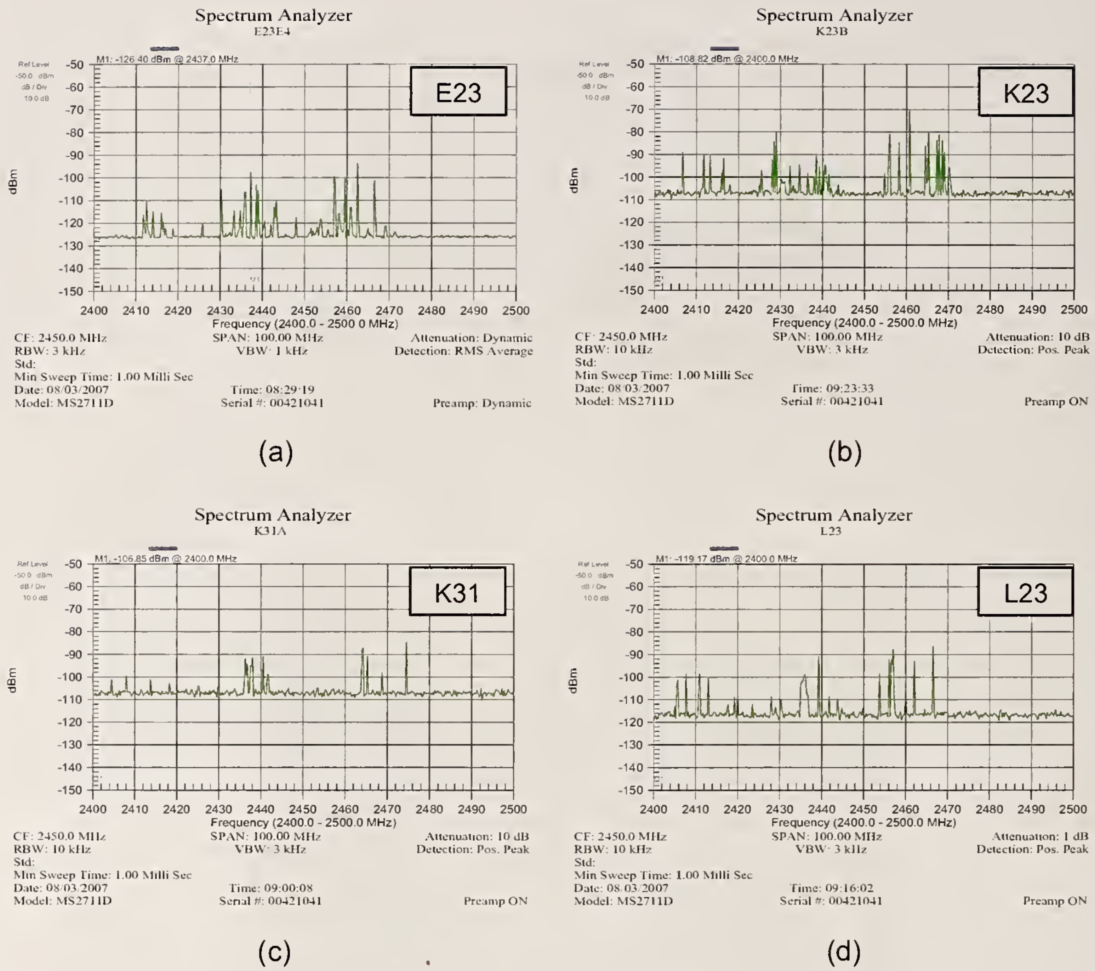


Figure 4-4: Handheld spectrum analyzer measurements collected over a one-minute period in the 2.4 GHz frequency band in the stamping plant. Signals are clearly present in the three primary WLAN channels throughout the plant, although in some cases they are quite weak.

We carried out similar tests at the engine plant. We again turned on the "peak hold" function on the spectrum analyzer and carried out the measurement over an approximately three-minute window to see what signals were present over a longer period. Figure 4-5 shows results from representative locations on the production floor. These data were collected on Sunday, August 5, 2007. A second set of data collected at the same locations on Monday, August 6, 2007 is shown in Figure 4-6.

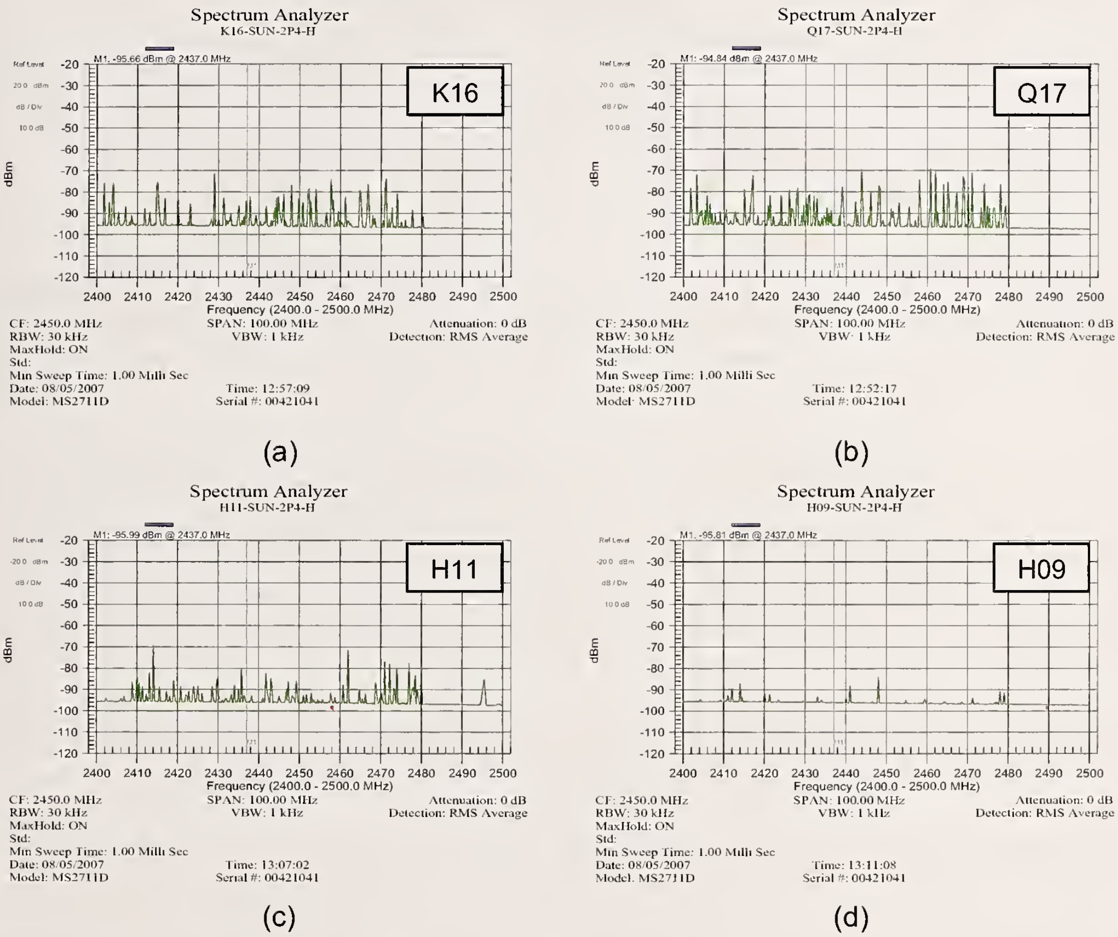


Figure 4-5: Handheld spectrum analyzer measurements collected over a three-minute period in the 2.4 GHz frequency band in the engine plant. As in the stamping plant, signals are present in the three primary WLAN channels throughout the plant. Other signals being transmitted in this frequency band are present in many locations as well.

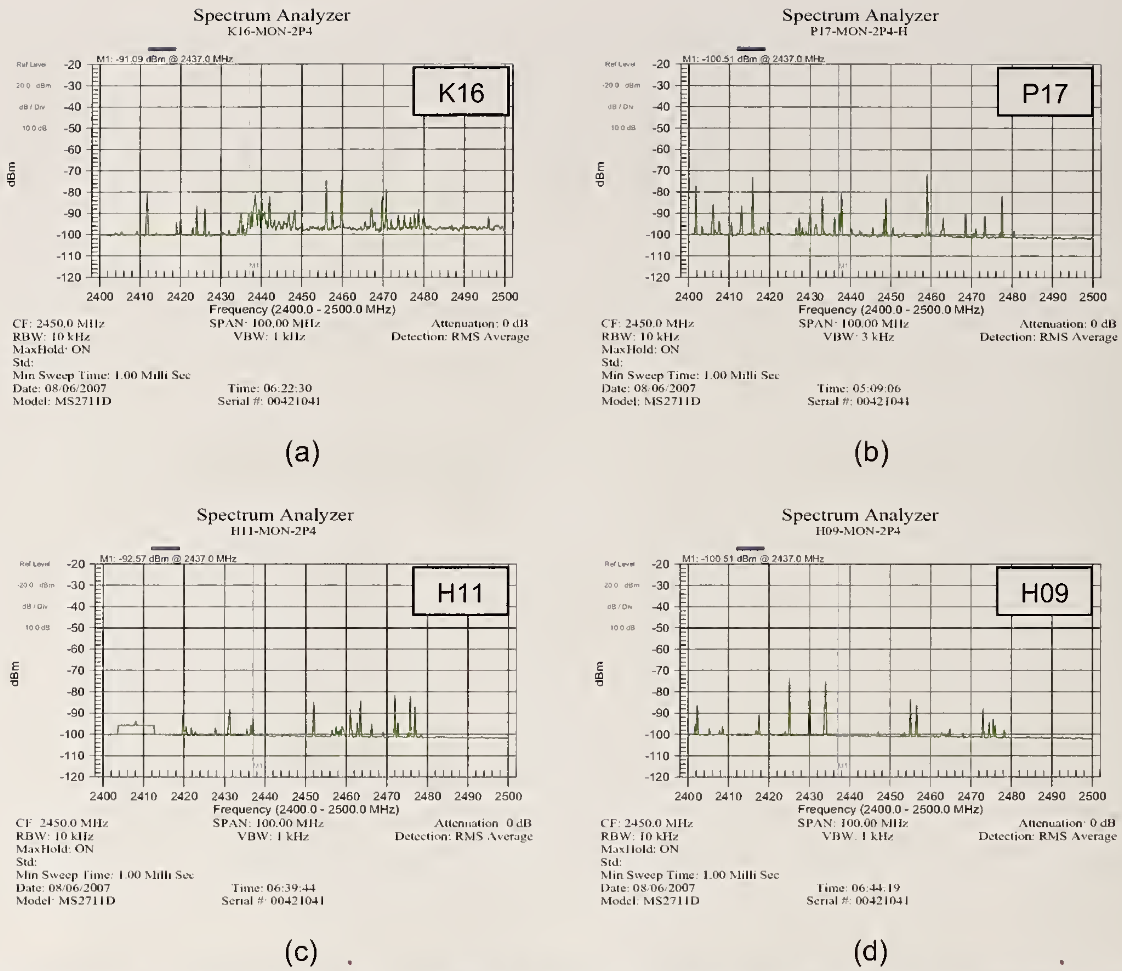


Figure 4-6: A second set of handheld spectrum analyzer measurements collected over a three-minute period in the 2.4 GHz frequency band in the engine plant. Again, signals are clearly present in the three primary WLAN channels, as well as at other frequencies in the band throughout the plant. The increased resolution in this set of graphs (10 kHz as opposed to 30 kHz in Figure 4-5) provides a reduced noise floor for the measurement, but also reduces the signal level in each measured frequency component, making the transient signals appear as lower-level signals compared to those in Figure 4-5, when they are probably comparable in actuality.

We also carried out some longer-term studies in the assembly plant. Figure 4-7 shows a typical snapshot of the WLAN traffic at a fixed receiving site during production. These data were collected over a 15-minute period during morning production on August 3, 2006. These measurements were carried out with a directional antenna aimed directly at one of the WLAN nodes. The 802.11b spectral mask has been drawn over the signals for channels 1, 6, and 11 (center frequencies of 2.412, 2.437, and 2.462 GHz), showing the approximate level of each received signal. The spectral mask simply shows the maximum allowed occupied bandwidth for 802.11b WLAN signals. The lines show the allowed frequency span and the level to which signals need to be attenuated outside the channel to prevent interference with neighboring channels.

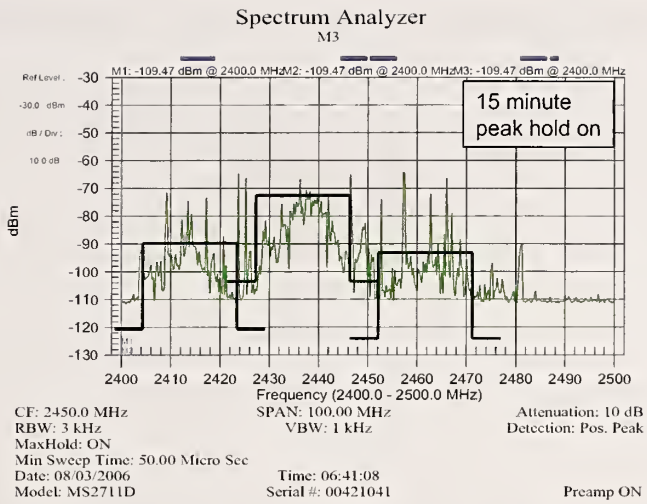


Figure 4-7: Handheld spectrum analyzer measurements collected over a 15 minute period in the 2.4 GHz frequency band. The spectral mask for the three 802.11b WLAN channels used in the facility are indicated on the graph, with the approximate level superimposed over the signals.

The high-level, spike-like signals seen in the channels adjacent to the center channel may be caused by other narrowband, frequency-hopping equipment in the vicinity such as a wireless scanning system used nearby. Also, the 802.11b protocol uses “probe” signals that allow nodes on different channels to communicate with each other. When examined over a long period, the probe signals show up as a set of narrowband spikes in adjacent channels. These spikes have approximately the same signal level as the main channel. Figure 4-8 shows three repeat measurements of a typical 802.11b card made in isolation in a NIST anechoic chamber over a one-hour period. The inset shows a single measurement, while the larger graph is the culmination of several measurements. The probe signals emanating from the card are clearly visible.

Finally, a comparison of received signal strength during production and during a break (Figure 4-9) at the assembly plant shows only slight changes in the level of activity in the 2.4 GHz band.

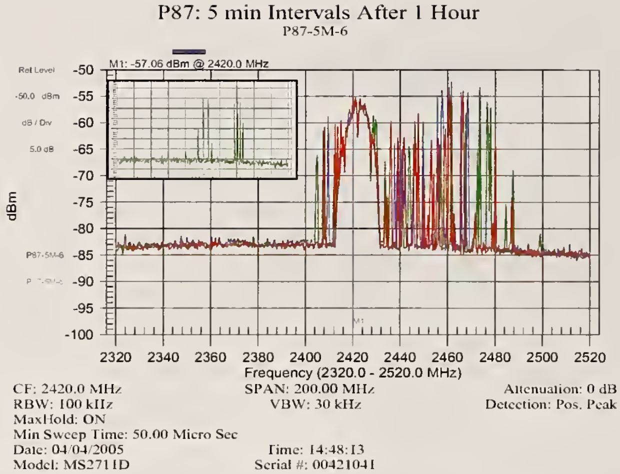


Figure 4-8: Handheld spectrum analyzer measurements of a representative 802.11b WLAN card made in isolation over a one-hour period. Note the large, spike-like signals outside the main channel which occur when the WLAN card monitors the environment for other cards in the area.

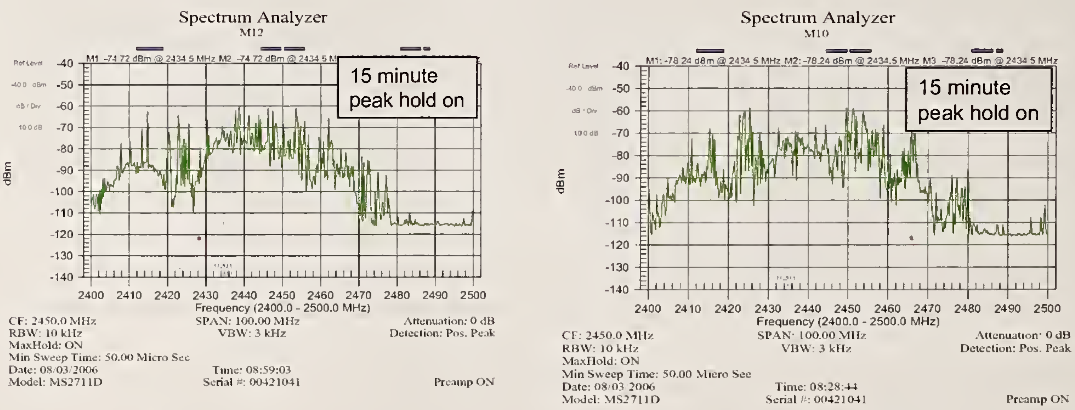


Figure 4-9: The left-hand graph shows activity in the 2.4 GHz band during production at the assembly plant, while the right-hand graph shows activity during a break.

The detailed measurements of the spectrum in the 2.4 GHz frequency band discussed here show that there is a significant level of activity in this band in all of the plants. The use of an unlicensed portion of the spectrum for critical operations can be problematic, since the activity level can be highly variable and so interference issues can arise intermittently. Personal electronics as well as other systems that operate in this band can interfere with operations. However, there are few licensed frequency bands available for broadband data transfer in industrial environments. Frequency and channel coordination, as is done at these facilities, are two good options to minimize interference issues. A third would be to occasionally monitor activity, such as we have done here. When the spectrum gets crowded or if interference issues arise, these types of tests can be very beneficial in identifying and eliminating sources of interference.

5. Ultra-Wideband Propagation Measurements

5.1 Measurement set-up

In order to characterize the radio-wave scattering in these facilities, we deployed a NIST-developed propagation measurement system. The system acquires both magnitude and phase of signals covering a broad range of frequencies. The phases of the sent and received signals are synchronized, enabling transformation of the recorded signal into the time domain. Signals that cover a wide frequency band transform to short-duration pulses in the time domain. Thus, this system can be used to study the effects of multiple reflections ('multipath') in an environment by measuring the time taken for reflections of the initial pulse to decay below a certain threshold value.

The measurement system consists of a precision vector network analyzer (VNA), a transmitting antenna, a receiving antenna, an 18 GHz analog optical link, and 50 Ω microwave cables to connect the antennas with the VNA, as shown in Figure 5-1. A laptop computer is connected to the VNA in order to control the measurement process and to acquire and store measured data. The VNA has a transmitter and receiver within the same instrument and performs measurements between the two antennas. We acquired both the magnitude and phase of the S-parameter S_{21}, which describes the characteristics of the transmission path. Data may be acquired at stepped frequencies over the range of 300 kHz to 18 GHz. For this series of tests, transmission data were acquired at approximately 80,000 frequencies. For frequencies up to 1 GHz, omnidirectional antennas were used. For frequencies from 1 GHz to 18 GHz, we used directional dual-ridge waveguide antennas, similar to horn antennas. The transmitting antenna was held fixed and the receiving antenna moved along aisles in the factory on a rolling cart, as shown in Figures 5-2 through 5-8.

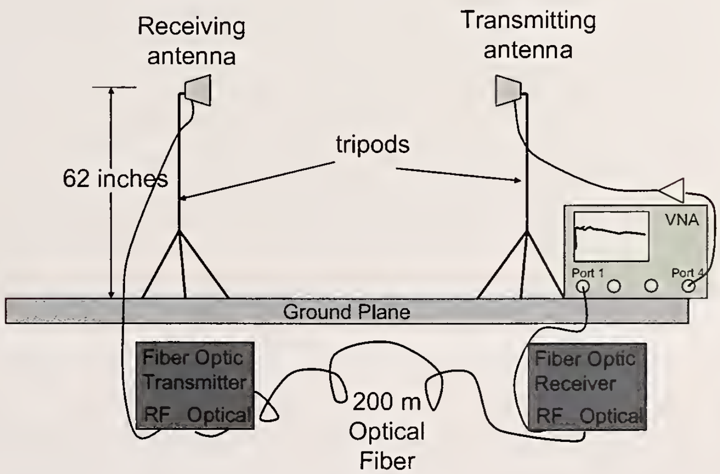


Figure 5-1: Ultrawideband, synthetic-pulse measurement system based on a vector network analyzer. Frequency-domain measurements, synchronized by the optical fiber link, are transformed to the time domain in post-processing. This enables determination of wideband path loss, time-delay spread and other figures of merit important in characterizing broadband modulated signal transmission.

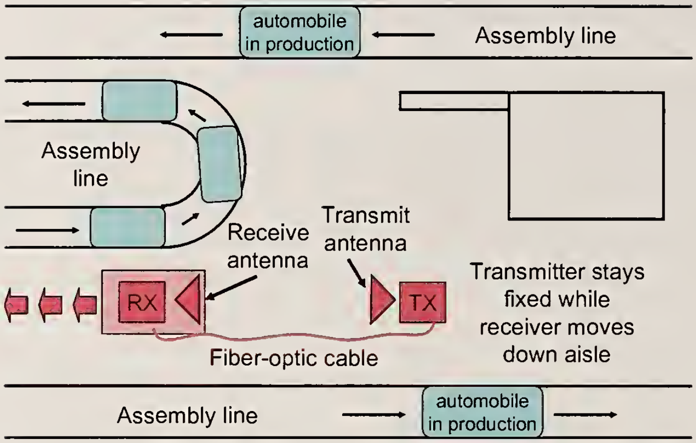


Figure 5-2: Layout of UWB tests in the assembly plant. The VNA (labeled "TX" for transmitter) remains in a fixed location. The signal received by the receive antenna (labeled "RX" for receiver) is amplified and returned to the VNA via a fiber-optic cable that maintains the phase relationships between measured frequency components. The receiver moves away from the transmitter along a straight line in discrete steps.

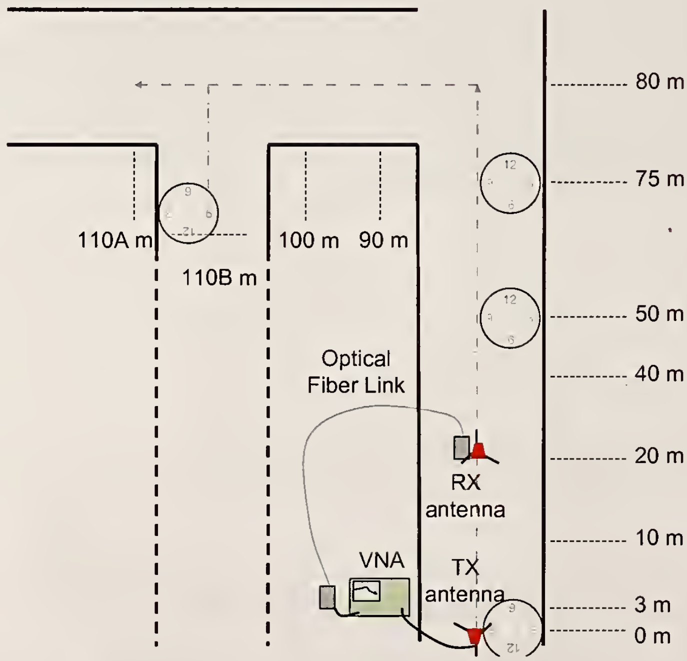


Figure 5-3: Layout of the NIST ultrawideband tests in the stamping plant. The receive antenna (RX) was placed on a rolling cart and moved along aisles H and G, as indicated on the layout given in Figure 2-1. Measurements were taken at the distances indicated above. The transmit antenna (TX) remain fixed. When directional antennas were used, at 0 m, 50 m, 75 m, and 110 m, the RX antenna was rotated in the directions indicated above.

Figure 5-4: Photograph of the long corridor in the stamping plant where the UWB scattering measurements were made. The low-frequency omnidirectional antennas are shown. The VNA is located near the NIST staff at the left side of the photo.

Figure 5-5: Photograph looking the other way in the same corridor of the stamping plant. The high-frequency directional antennas are shown. The photograph shows the VNA and the optical fiber linking the transmitting and receiving antennas.

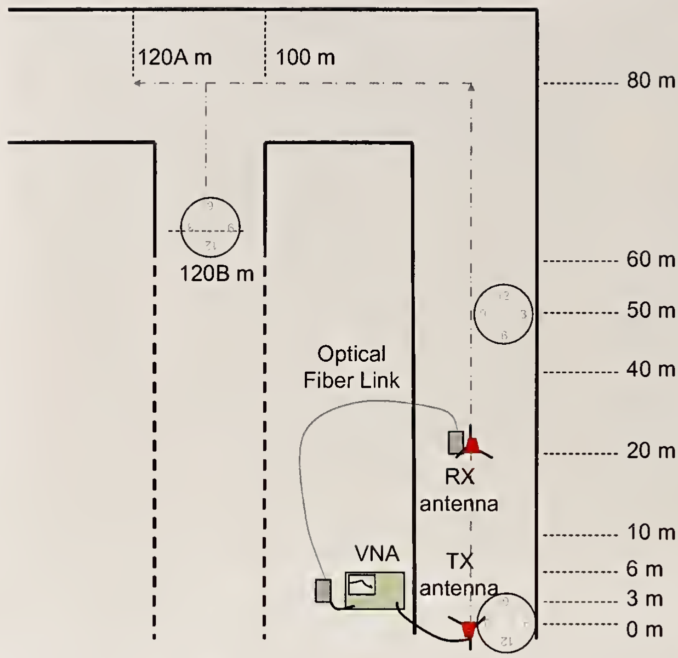


Figure 5-6: Layout of the NIST ultrawideband scattering tests used in the engine plant. The receive antenna (RX) was placed on a rolling cart and moved along aisles Q and P as indicated on the layout given in Figure 2-2. Measurements were taken at the distances indicated above. The transmit antenna (TX) remain fixed. When directional antennas were used, at 0 m, 50 m, and 120 m, the RX antenna was rotated in the directions indicated above.

Figure 5-7: Corridor in the engine plant where UWB scattering measurements were made. The receive antenna moved along the corridor on the rolling cart. The VNA and the transmitting antenna were located behind the photographer.

Figure 5-8: VNA set-up in the engine plant. The directional transmit antenna is shown in the foreground. The corridor shown in Figure 5-7 continues to the left side of this picture.

Note that throughout this work, measurement uncertainties are not reported. End users of this data are primarily interested in large-scale statistical behavior on the order of tens of decibels, thus including uncertainties on the order of 1 dB is of little value.

5.2 Frequency-domain measurements

We first looked at measurements of received signal levels in the frequency domain. Figures 5-9 and 5-10 show measured excess path loss for the stamping plant and engine plant, respectively, where the data have been normalized to the magnitude of the direct-path received signal. The term "excess" means the direct-path signal has been subtracted, so we are looking only at scattered signals. In cases where there is no direct-path signal, we estimate its value by measuring free-space path loss for closely spaced antennas at a known distance. Knowing the free-space path loss for a given set of antennas and cables, we can then predict its value at other distances, since the free-space path loss has a $1/r$ dependence, where r is the distance in meters.

Figures 5-9 and 5-10 show results for frequencies from 1 GHz to 18 GHz at four locations in the stamping plant and engine plant, respectively. All frequency components were transmitted at the same amplitude level, but the received signals show a range of amplitude values. The variations in received signal level across the measured frequency span indicate that signals reflected (scattered) off metallic surfaces and walls in the plants are interfering with the received signal. This is very pronounced at the 50 m distances, where interference off of a major reflecting surface (a corridor in the stamping plant and a wall in the engine plant) occurs at the 50 m mark. Once the receiving antennas turn the corner and are no longer within line of sight of the transmitting antennas, the signal levels drop and become much more noisy. This is because the large number of reflected paths taken by the signals between transmitter and receiver behave statistically like noise when there is no direct signal component. We saw similar results for the low-frequency omnidirectional antennas. The complete set of excess-path-loss data are given in the appendices at the end of the report.

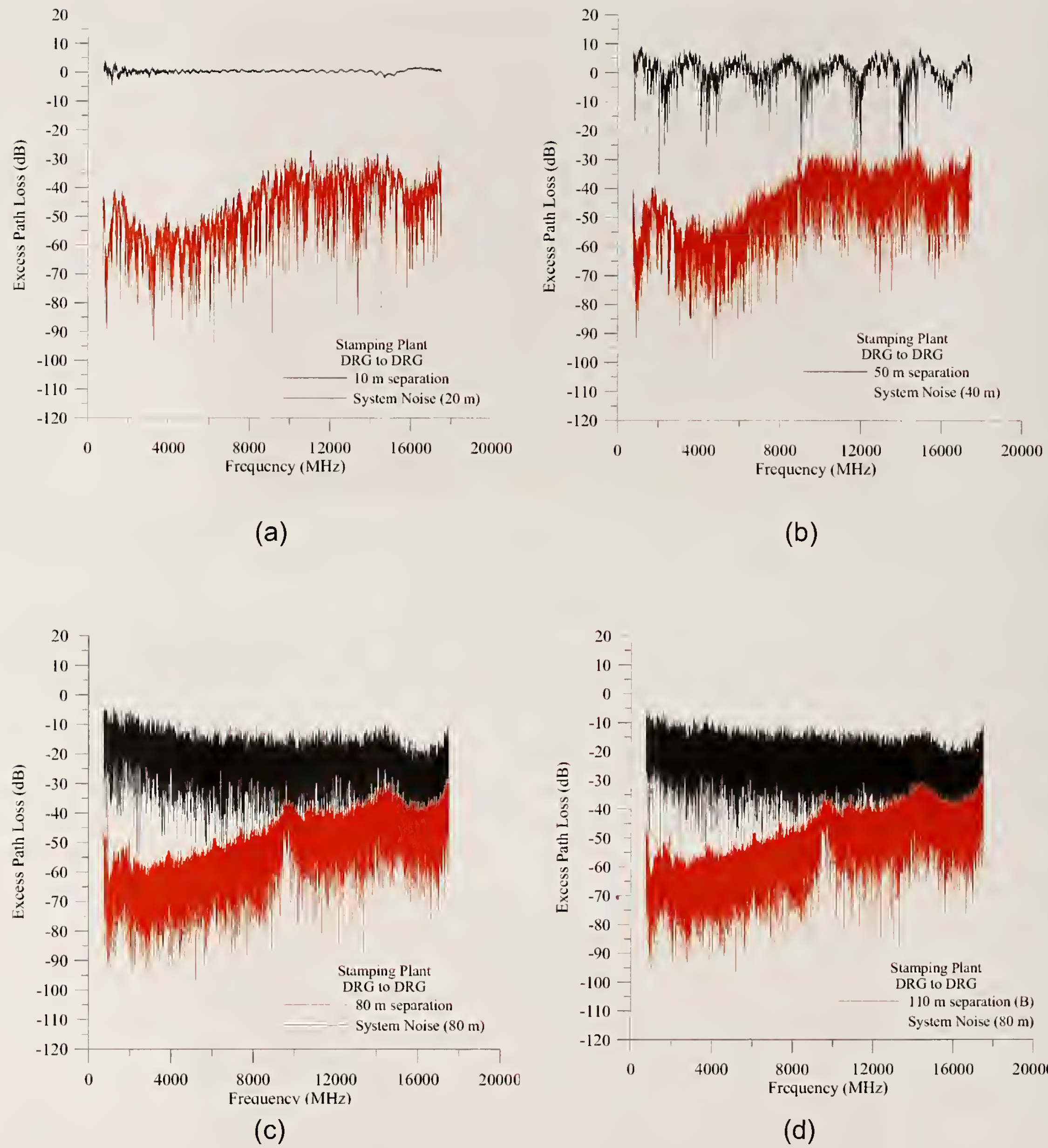


Figure 5-9: UWB measurements made at the stamping plant using directional antennas facing each other at distances of (a) 10 m, (b) 50 m, (c) 80 m, and (d) 110 m. The deep nulls in (b) indicate significant scattering. The low-level, noise-like signals in (c) and (d) mean that interference and loss are creating a very noisy environment.

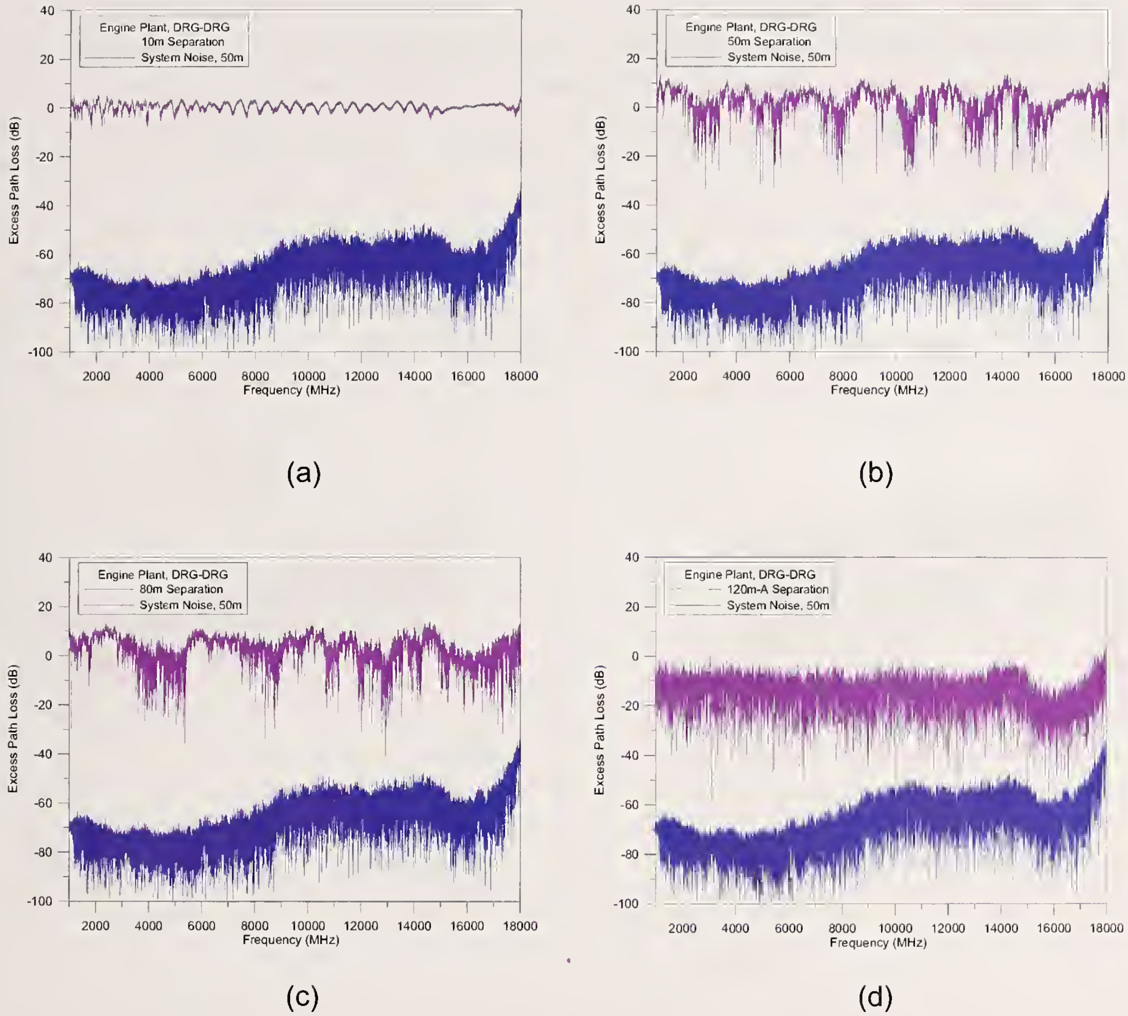


Figure 5-10: UWB measurements made at the engine plant using directional antennas facing each other at distances of (a) 10 m, (b) 50 m, (c) 80 m, and (d) 120 m. The deep nulls in (b) and (c) indicate significant scattering. The low-level, noise-like signals in (d) mean that interference and loss are creating a very noisy environment.

5.3 Time-domain data

As mentioned above, the ability to acquire both magnitude and phase data over a large number of frequencies makes it possible to perform post-processing where we mathematically transform the stepped-frequency data into high-resolution, time-domain waveforms. These, in turn, can be gated and filtered to isolate selected scattering events. They can also be used to find wireless system figures of merit such as the power delay profile of an environment, the *K*-factor, and RMS delay spread.

Post-processed time-domain waveforms that illustrate the multiple reflections scattered by equipment and structures are shown in Figure 5-11. The initial waveform

event is the direct coupling between the transmit and receive antennas. The waveform activity that follows corresponds to scattering from objects inside the plants. The waveforms generally have exponentially decaying envelopes that are caused by lossy materials inside the plants (e.g., manufactured products, machinery, concrete, etc.).

The fact that the plants exhibit such significant scattering behavior can pose a challenge for indoor wireless communications. One metric that is used to quantify this effect is the RMS delay spread, which is the period required for the reflected signals to die down below a certain threshold level. RMS delay for the synthetic pulse measurements is defined in [3]. A long RMS delay spread means that scattering is significant. When the RMS delay spread exceeds the error correction of the digital modulation used in most wireless transmissions, errors in transmitted bits may occur.

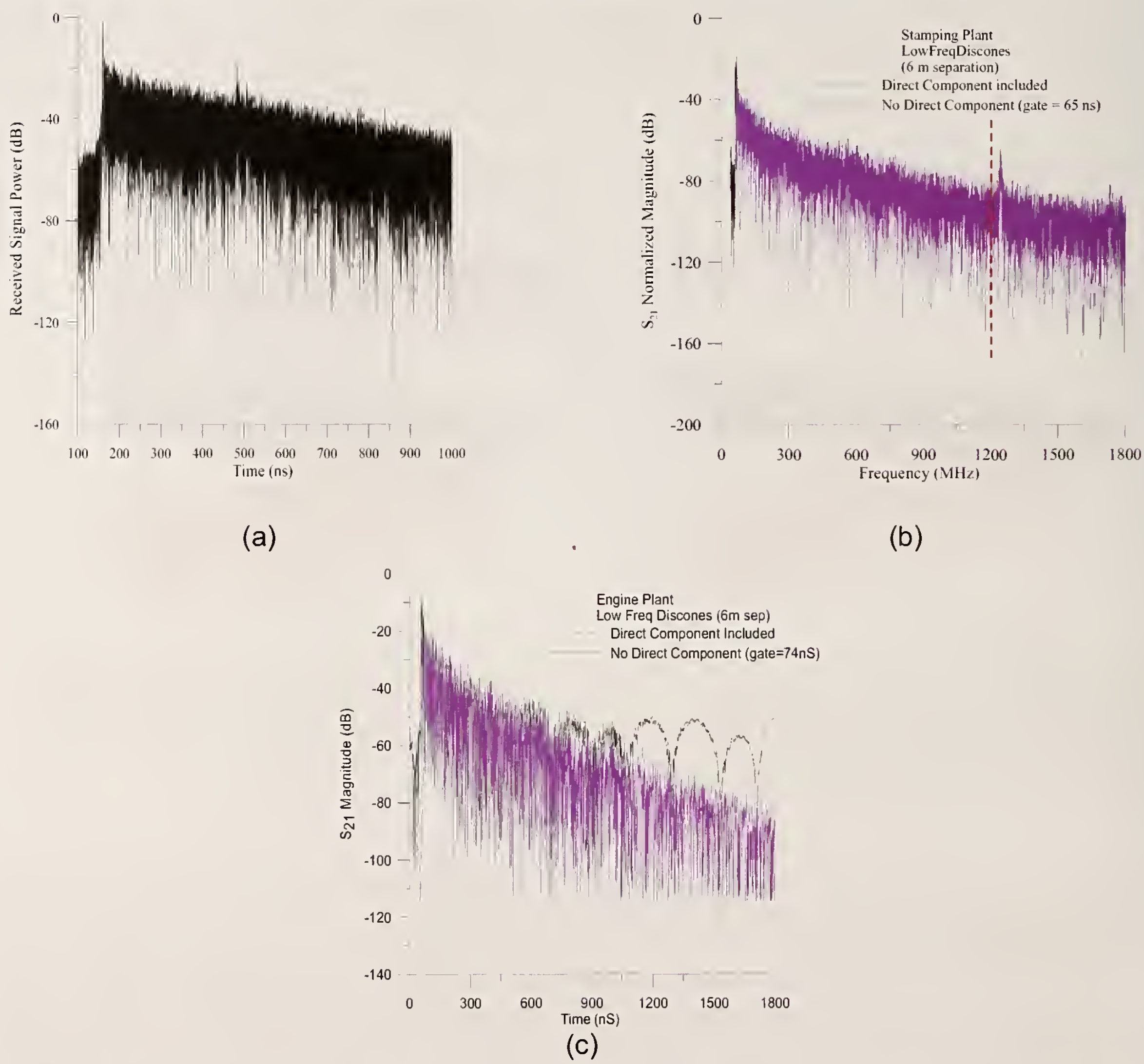


Figure 5-11: Time-domain response for antenna-to-antenna separations of (a) 50 m in the assembly plant; (b) 6 m in the stamping plant; (c) 6 m in the engine plant. Note the large reflection from a truck loading door in the assembly plant measurement.

Post-processing of the measured VNA data readily yields the RMS delay spread. Tables 5-1 and 5-2 give the RMS delay spread values that we measured in the stamping plant and the engine plant, respectively, for both high-frequency and low-frequency antennas.

Table 5-1:
Stamping plant
Low-frequency, omnidirectional

Position (m)	RMS Delay Spread (ns)	Mean Delay (ns)
6*	61	34
10*	76	50
20*	103	73
40*	117	72
50*	173	118
60*	142	117
75*	139	101
80	128	107
90	130	136
100	146	173
110A	153	220
110B	153	218

Table 5-2:
Stamping plant
High-frequency, directional antennas

Position (m)	RMS Delay Spread (ns)	Mean Delay (ns)
6*	62	19
10*	90	49
20*	75	30
40*	64	22
50*	75	33
60*	78	36
75*	79	37
80	106	97
90	97	88
100	104	117
110A	116	153
110B	131	158
110B elevated	128	165

* The positions with an asterisk indicate calculations where the direct component has been removed and the RMS delay spread calculated to a stop time of 900 ns, where the signal levels are approximately 20 – 40 dB above the noise floor of the instrument.

If we further post-process the results, we can find the resulting reverberant cavity quality factor Q. Cavity Q is one metric that is indicative of complex cavity behavior: the higher the Q, the more reverberant the cavity and the longer the decay time. Q is defined as

$$Q=2\pi\tau f, \tag{5-1}$$

where τ is the received-power decay time, and f is the center frequency of interest. The rate of decay is defined as the time it takes for the signal to decay to 37 % of its initial value.

Table 5-3:
Engine plant
Low-frequency, omnidirectional

Position (m)	RMS Delay Spread (ns)	Mean Delay (ns)
10*	66	36
20*	61	38
40*	107	77
50*	105	75
60*	116	93
80*	112	82
100	129	185
120A	133	208
120B	142	145

Table 5-4:
Engine plant
High-frequency, directional antennas

Position (m)	RMS Delay Spread (ns)	Mean Delay (ns)
6*	16	2
10*	29	4
20*	40	9
40*	51	11
50*	53	11
60*	57	13
80*	58	13
100	115	141
120A	114	155
120B	120	157

* The positions with an asterisk indicate calculations where the direct component has been removed and the RMS delay spread calculated to a stop time of 900 ns, where the signal levels are approximately 20 – 40 dB above the noise floor of the instrument.

Figure 5-12 depicts the decay characteristics in the assembly plant for frequencies in the vicinity of 950 MHz, 2.45 GHz, and 5.2 GHz. The decay times vary from 127 ns to 170 ns, with Q values covering a range of 1015 to 4149. This high-Q, reverberant behavior results primarily from the all-metal enclosure of the building and exhibits characteristics similar to some laboratory-based reverberation chambers.

A reverberant environment, such as this, produces much scattering in addition to the direct path between a transmitter and receiver and inhibits the ability to communicate. One metric used to quantify this effect is the K-factor, which is the ratio of the energy in the direct-path coupling between the transmit and receive antennas to the energy that results from environmental reflections. A high K-factor means that the antenna-to-antenna coupling dominates, and a low K-factor implies a strongly reverberant (high multipath) environment.

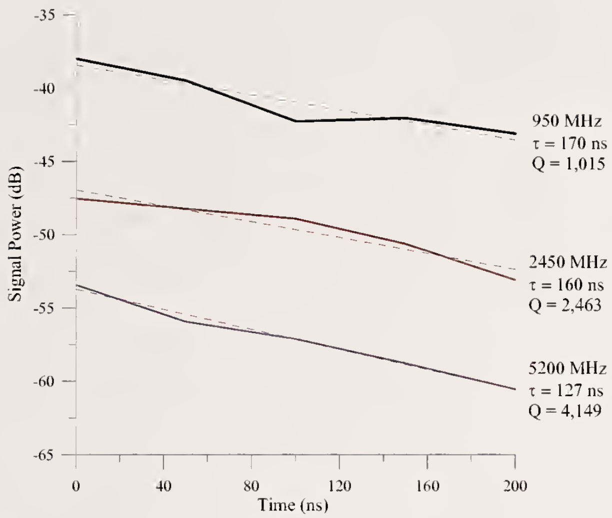
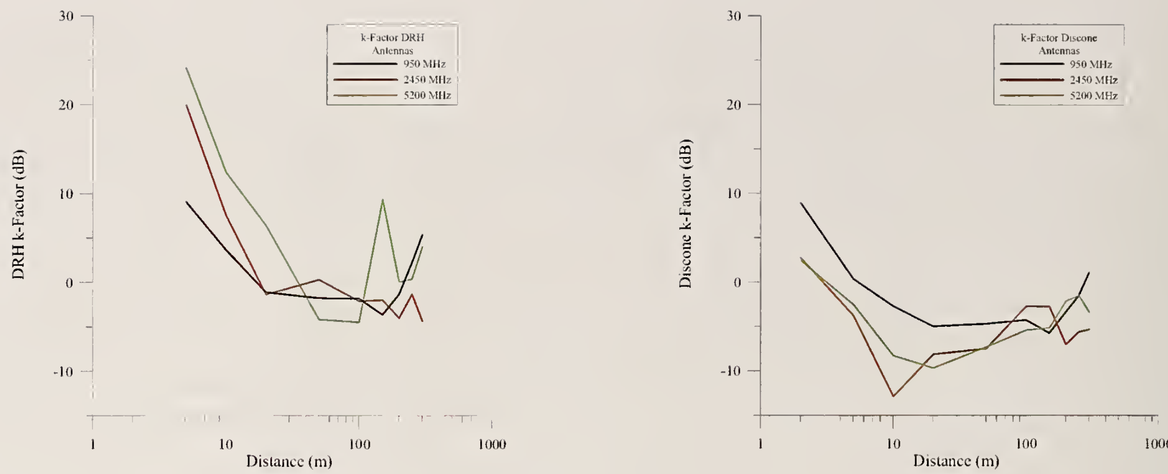


Figure 5-12: Time-domain response for a 50 m antenna separation in the assembly plant using an omnidirectional transmit antenna. Decay characteristics are shown at selected wireless frequencies using a 200 MHz averaging bandwidth.

We post-processed the VNA data to find the *K*-factor of the assembly plant. Figure 5-13 (a) and (b) depict *K*-factors measured in the assembly plant as function of antenna separation from 2 m – 300 m. We used both directional (Figure 5-13(a)) and omnidirectional (Figure 5-13(b)) transmit antennas. The curves are smoothed out by use of frequency averaging over a bandwidth of 200 MHz. Results are plotted in decibels for the 950 MHz, 2.45 GHz, and 5.2 GHz wireless bands.

For the case of the directional transmit antenna (Figure 5-13(a)), the *K*-factor increases significantly for antenna separations less than 20 m. A more rapid increase is noted at the higher frequencies due to the higher gain of the transmit antenna and improved directionality. As the antenna separation is increased beyond 20 m, the *K*-factor generally stays in the vicinity of unity (0 dB). We note a peak in the 5.2 GHz data at 150 m, which might be due to a combination of antenna pattern effects and a strongly reflecting path between transmitter and receiver. A similar effect is seen for the 950 MHz data.



(a) (b)

Figure 5-13: *K*-factor over a 200 MHz bandwidth as a function of distance in the assembly plant for three different center frequencies. Black: 950 MHz, Red: 2.45 GHz, Green: 5.2 GHz. (a) Directional antennas. (b) Omnidirectional antennas.

The situation changes when the transmit antenna is omnidirectional, as shown in Figure 5-13(b). The *K*-factor now drops to unity or less (< 0 dB) as distance is increased beyond 5 m. At a distance of 100 m or more, some peaks in the *K*-factor occur. This is probably due to a combination of the effects of the antenna pattern and the occurrence of strong environmental scattering. Lower values of *K*-factor indicate that the reverberant behavior of the assembly plant is much stronger if we illuminate it with an omnidirectional antenna. We also see that the use of a directional antenna reduces the effects of scattering and multipath for transmitter/receiver separations of 20 m or less. For larger separations, however, the advantages of using a directional antenna diminish rapidly.

Figures 5-14 (a) through (d) depict the *K*-factor as a function of frequency for both the directional and non-directional antenna types. Each curve corresponds to a different transmit/receive antenna separation. Results are plotted over a frequency range from 1 GHz to 10 GHz using an averaging bandwidth of 200 MHz.

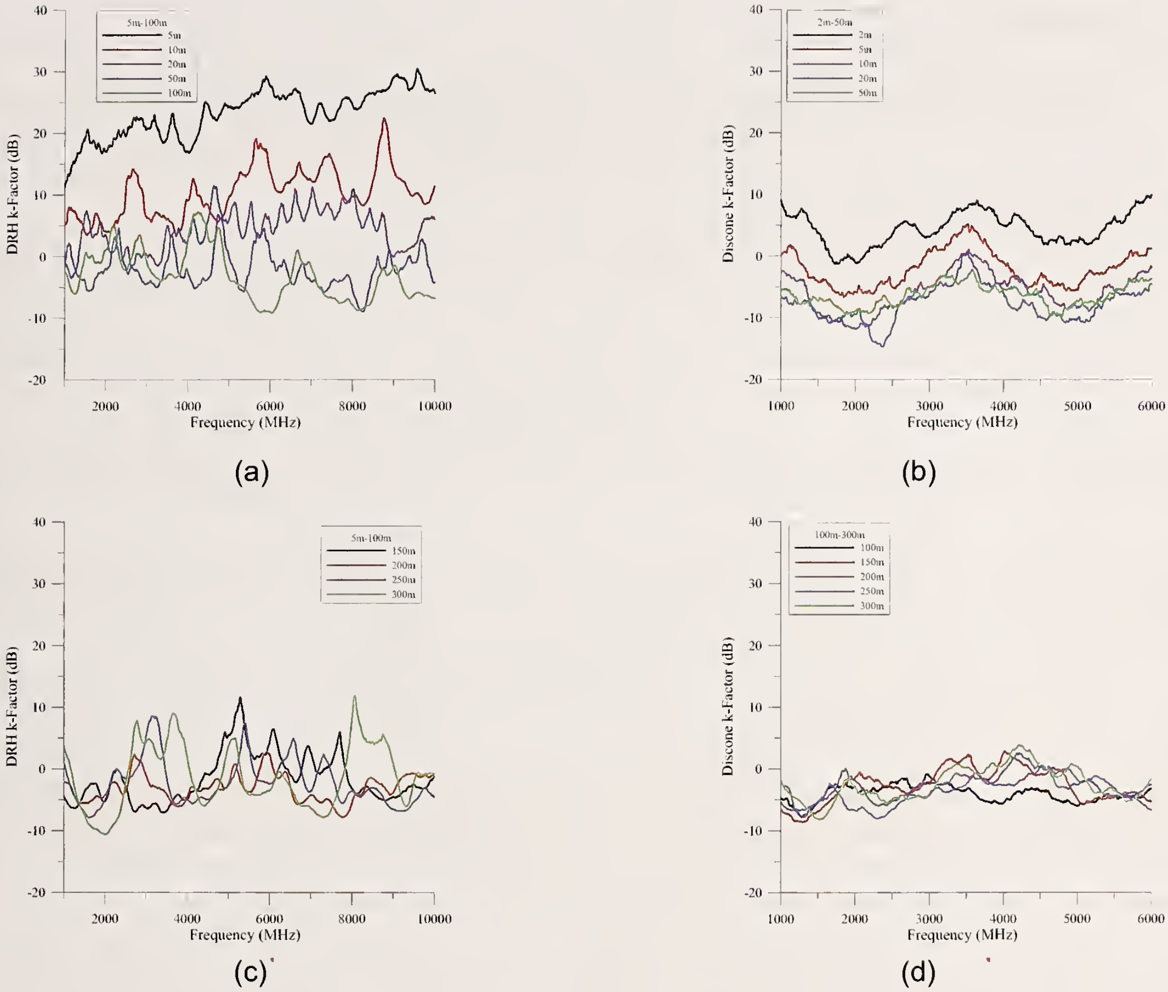


Figure 5-14: *K*-factor as a function of frequency for various antenna spacings in the assembly plant. (a) Directional antennas (5 m to100 m). (b) Omnidirectional antennas (2 m to 50 m). (c) Directional Antennas (150 m to 300 m). (d) Omnidirectional antennas (100 m to 300 m). Averaging bandwidth was 200 MHz.

In Figures 5-14(a) and 5-14(c), we see rapid variations in received-signal level as a function of frequency for the directional antennas. These variations are caused by the more complex pattern characteristics of the directional antennas. Peak-to-peak variations are typically in the range of 15 dB to 20 dB. The corresponding results for an omnidirectional transmit antenna, shown in Figures 5-14(b) and 5-14(d), exhibit smoother variations with frequency, due to the simple pattern characteristics. Peak-to-peak variations in the *K*-factor of 5 dB to10 dB are typically seen as a function of frequency. The effects of using different types of antennas on received signal levels can be seen in more detail in the appendices, where the complete set of excess-path-loss data is given.

5.4 Conclusion

The three buildings studied here exhibit complicated scattering and multipath propagation as functions of both distance and frequency. These characteristics are due to a combination of metallic walls and ceilings, concrete floors, and a multitude of metallic scatterers inside the plants.

One example of the complicated nature of radio-wave propagation in these facilities is well illustrated by the interference patterns seen in the UWB measurements of Figures 5-9 and 5-10. The signals emitted from our antennas were constrained to propagate down the aisleways by the antennas that we used and by the metallic structures on either side of the aisle. Very little energy was transmitted up and over the structures lining the aisles. Thus, under line-of-sight conditions, signals sometimes experienced deep interference nulls when the receiver was located midway between the transmitter and a reflecting surface such as a wall or even a perpendicular corridor, as shown in Figures 5-9(b) and 5-10(b). When the receiver was located around the corner from the transmitter, radio-wave penetration through the metallic structures in the plants was not possible. As a result, in non-line-of-sight conditions, signals were attenuated and exhibited classical, noise-like, Rayleigh-distributed behavior.

The UWB measurements also showed that the use of directional antennas reduced the RMS delay spread. We saw this in the stamping and engine plants, the only two facilities where we calculated RMS delay spread. The RMS delay spread in the engine plant was significantly longer than that of the stamping plant, highlighting the more open floor plan in the engine plant. Reflections take longer to die out in this environment. When delay spread becomes long enough, it can interfere with the error correction in the transmission and additional errors can occur.

The impact on wireless communications will depend on the type of system, data rate, and the location of the transmitter(s) and receiver(s). The representative measurements provided here of excess path loss, RMS delay spread, and *K*-factor are useful parameters that we hope will guide the design of wireless communications systems in these types of plants.

6. Summary

Our background ambient measurements offered a few surprises. While they showed expected significant transmission activity in the 2.4 GHz unlicensed ISM frequency bands, there was essentially no activity in the 5.8 GHz band at the engine plant, and little in the 900 MHz frequency band in either plant. As expected, we saw transmissions from external sources such as broadcast stations and cellular telephone traffic. Since these are in frequency bands outside the operational bands of interest, they do not currently cause interference to operations. Finally, we saw some unintentionally generated machine noise at low frequencies within the stamping plant. This unintentionally transmitted noise can affect systems that operate at lower frequencies, such as diagnostics used in automotive applications.

The site-specific spectrum analyzer measurement results showed that wireless transmissions in the 2.4 GHz frequency band can be detected at most locations throughout these two facilities. This indicates that transmitting and repeating nodes have been successfully installed throughout the plants.

UWB scattering measurements show that these facilities are highly reflective, reverberant environments that can complicate reliable performance of wireless technology. While the existing wireless technology has been successfully deployed, future expanded use of wireless for control and telemetry operations could pose an interference problem if the environment is not considered.

There are several methods that can be implemented to minimize the effects of the reflective environment. Some are operational in nature, some deal with changing the environment, and some are technology based. Examples of these methods include:

Operational

- Use licensed frequency bands where possible
- Coordinate frequency and channel usage
- Restrict or forbid use of personal electronics in key frequency bands (e.g., 2.4 GHz band)

Environmental

- Install absorbing material in the proximity of local wireless systems such as controllers
- Place additional nodes at key locations

Technological

- Use wireless systems having high immunity to electromagnetic interference
- Use wireless systems designed to operate in high multipath environments
- Employ equipment on the production floor that emit little machine noise
- Use directional antennas where appropriate

The results of this and the prior study at the assembly plant will be used to generate improved statistical models that describe the RF nature of the production floor for wireless systems. These models may be used by telecommunications manufacturers to engineer more robust designs for communications equipment, as well as for development of improved standards specifically for the automotive industry.

Also, based on the measured results from the three automotive plants we have tested, work is currently underway at NIST to develop laboratory-based test methods to prequalify wireless devices for deployment on the factory floor. The test methods are based on measuring a device's functionality when placed in a reverberation chamber whose characteristics have been tuned to simulate those of the factory floor. If a device operates properly in the test chamber, engineers can be confident that it would operate on the factory floor as well.

Partial funding and support for this work was provided by the NIST United States Council for Automotive Research (USCAR) Liaison Dr. John Slotwinski, NIST Manufacturing Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899-8200.

7. References

[1] IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band, IEEE Standard 802.11b™-1999.

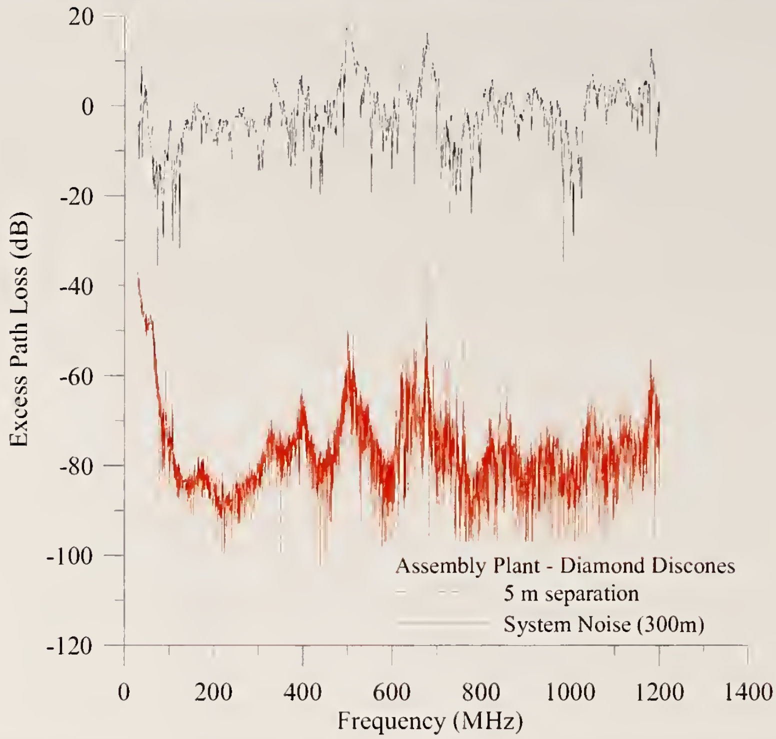
[2] IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5 GHz Band, IEEE Standard 802.11a™-1999.

[3] K.A. Remley, G. Koepke, C.L. Holloway, C. Grosvenor, D. Camell, J. Ladbury, D. Novotny, W.F. Young, G. Hough, M.D. McKinley, Y. Becquet, J. Korsnes, "Measurements to Support Broadband Modulated-Signal Radio Transmissions for the Public-Safety Sector," *Natl. Inst. Stand. Technol. Note 1546*, Apr. 2008.

Appendix A: Assembly Plant, Low-Frequency Data, Omnidirectional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the assembly plant covering a frequency range of 100 MHz to 1.2 GHz when omnidirectional transmit and receive antennas were used.

Assembly Plant: Omnidirectional antennas



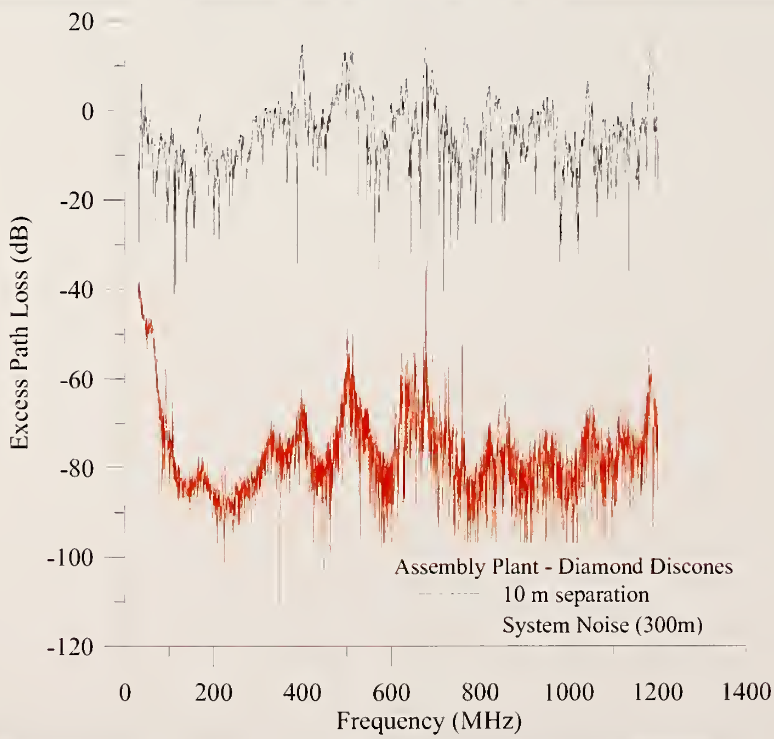
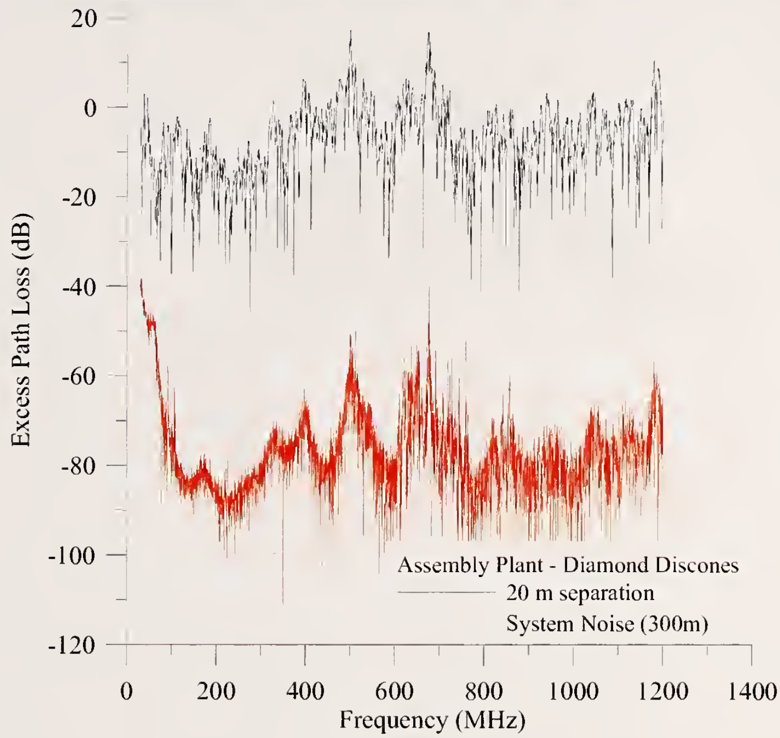


Figure A.1: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 5 m separation. Bottom: 10 m separation.

Assembly Plant: Omnidirectional antennas



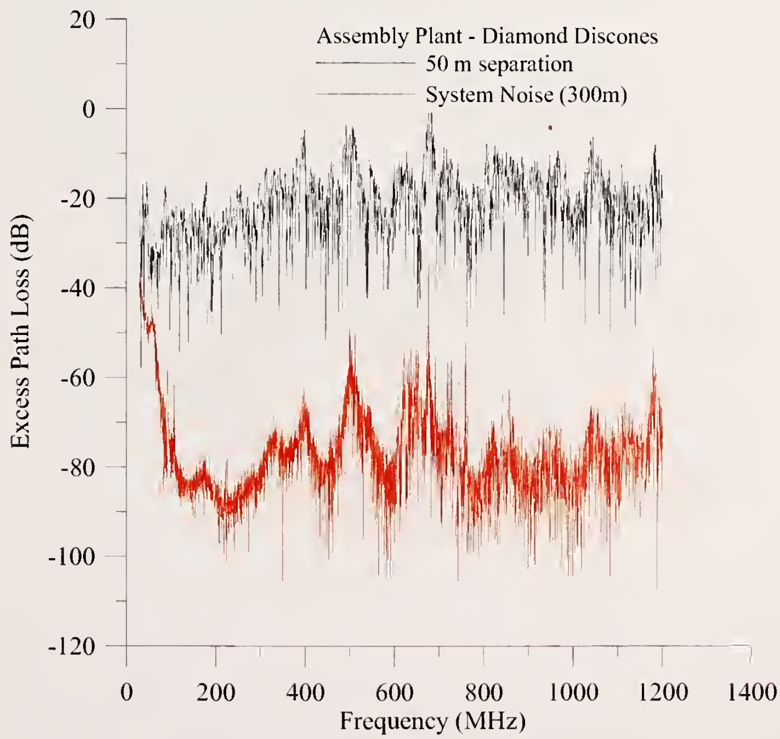
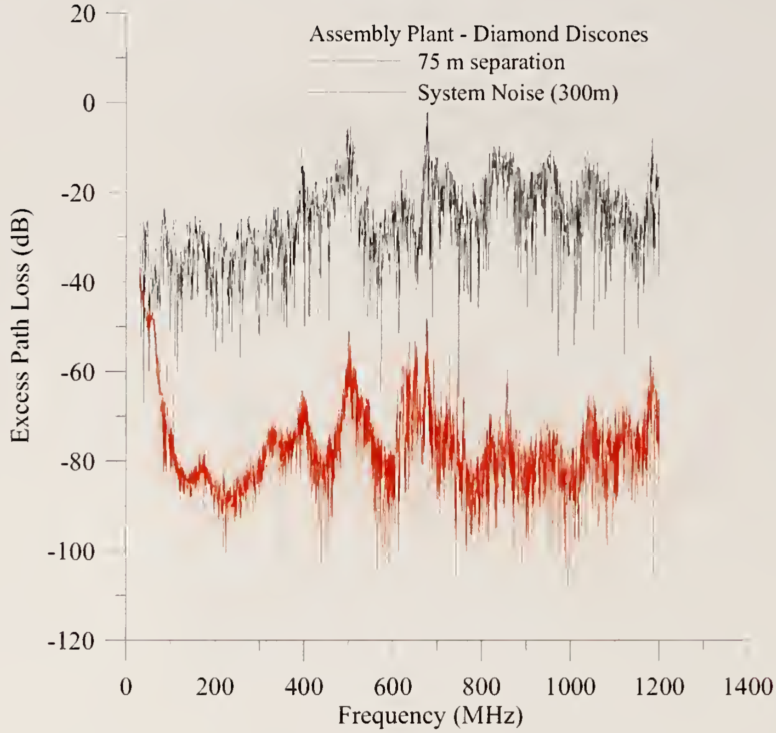


Figure A.2: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 20 m separation. Bottom: 50 m separation.

Assembly Plant: Omnidirectional antennas



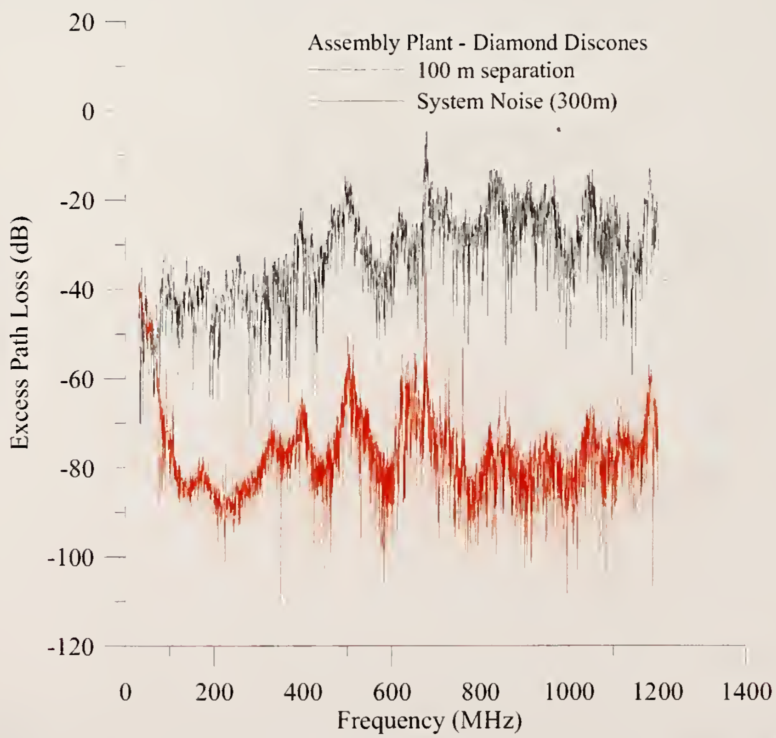
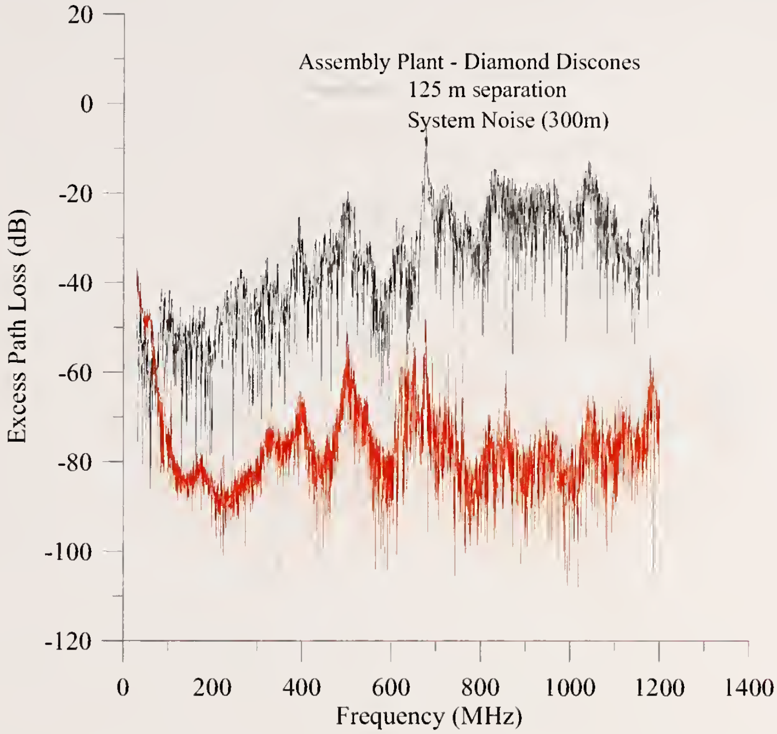


Figure A.3: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 75 m separation. Bottom: 100 m separation.

Assembly Plant: Omnidirectional antennas



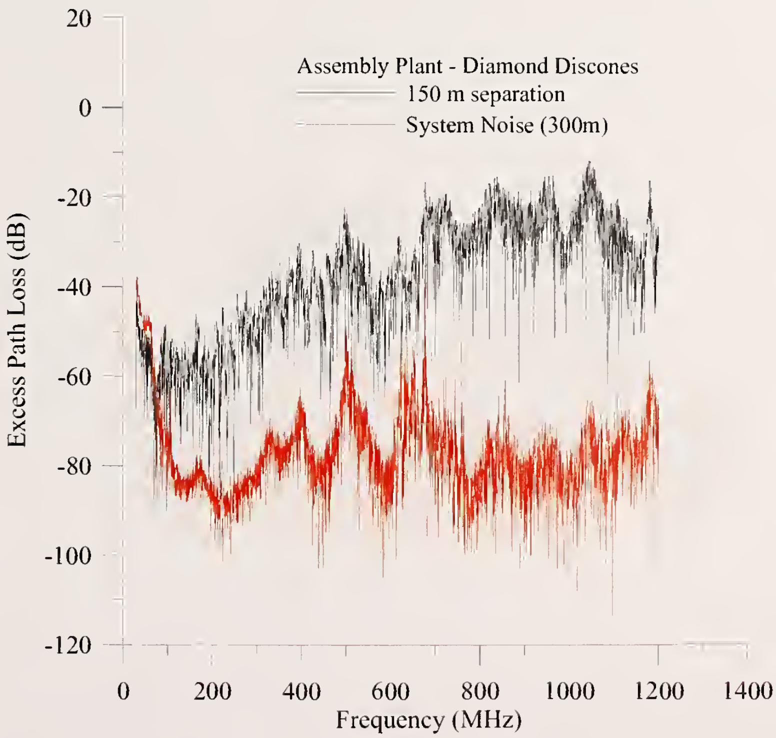


Figure A.4: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 125 m separation. Bottom: 150 m separation.

Assembly Plant: Omnidirectional antennas

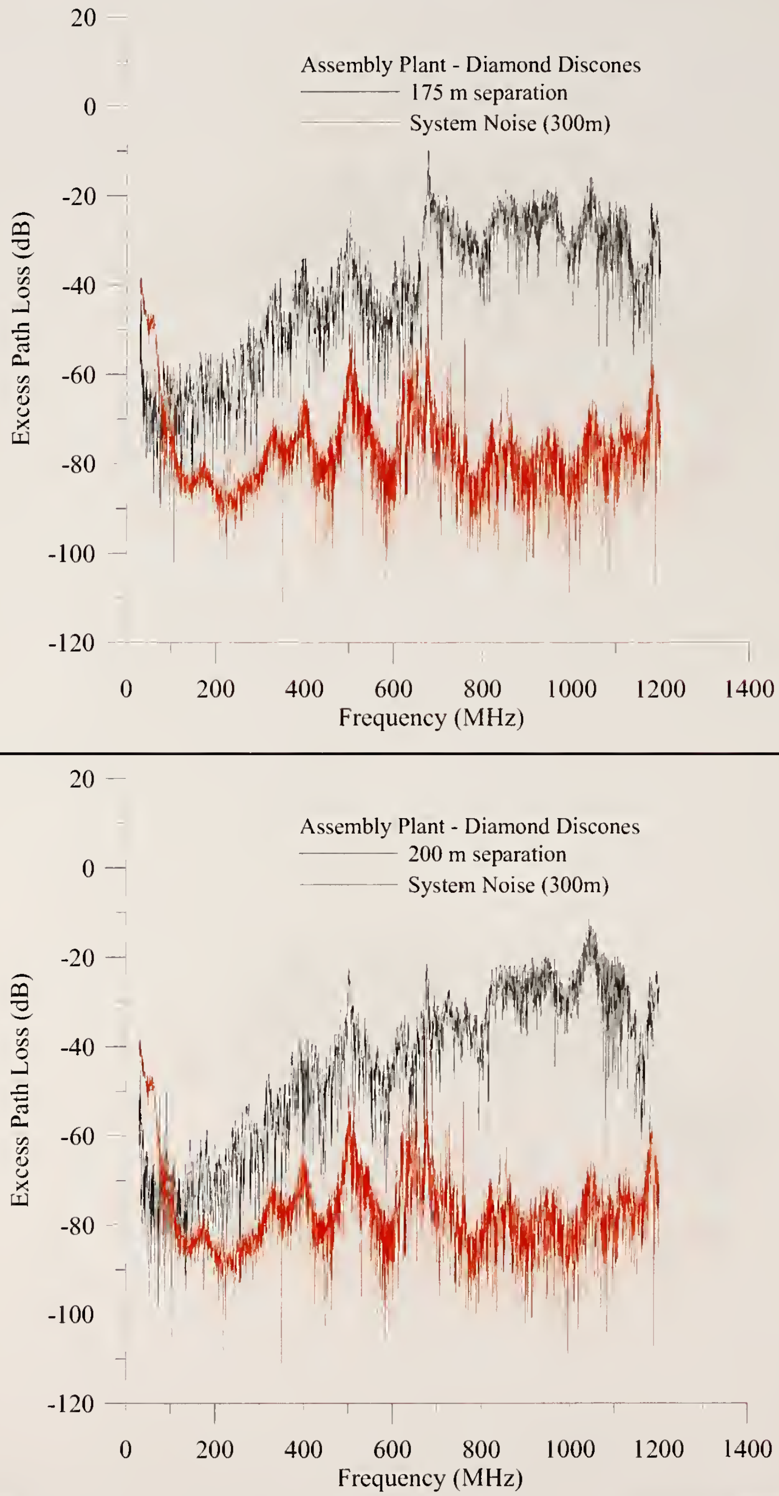
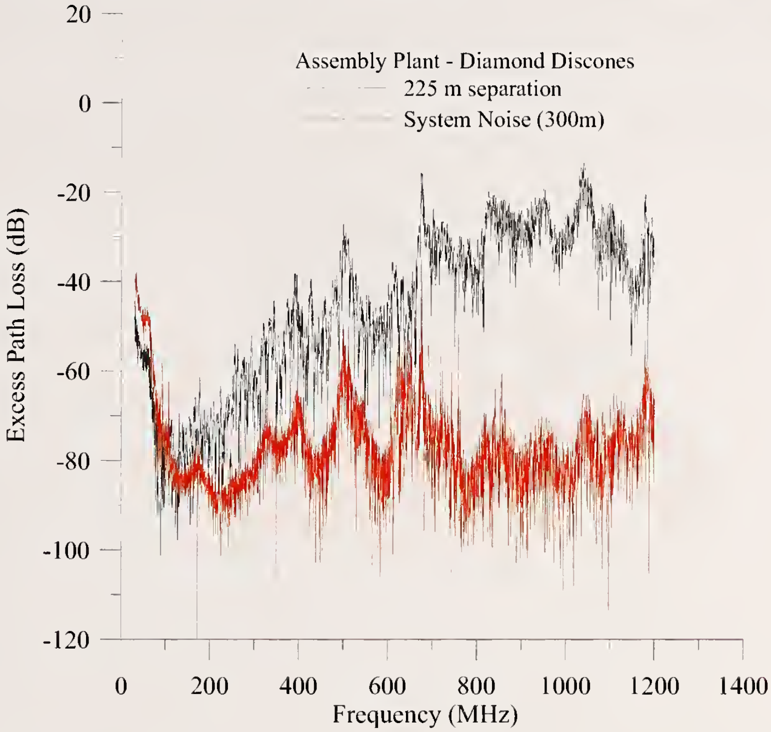


Figure A.5: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 175 m separation. Bottom: 200 m separation.

Assembly Plant: Omnidirectional antennas



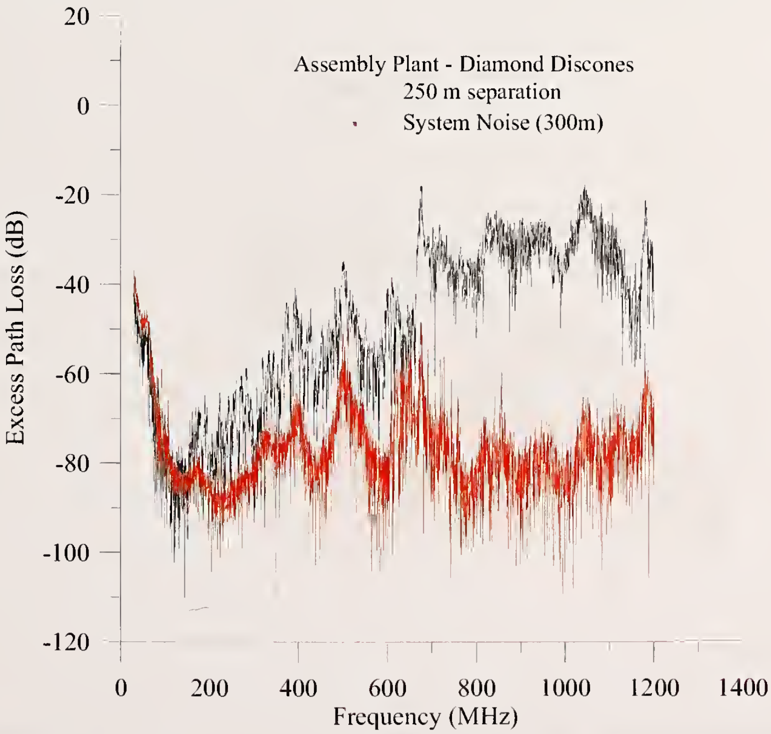
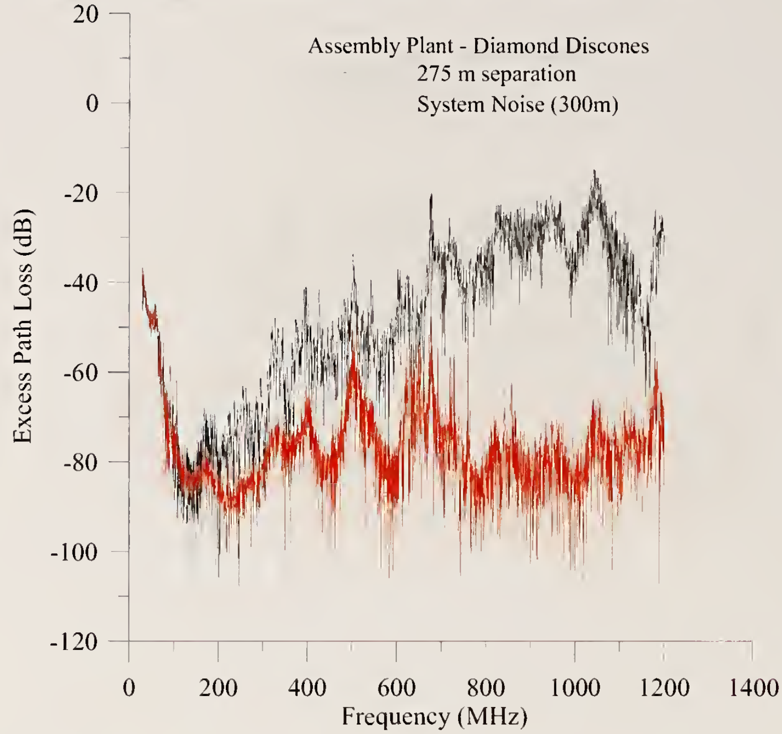


Figure A.6: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 225 m separation. Bottom: 250 m separation.

Assembly Plant: Omnidirectional antennas



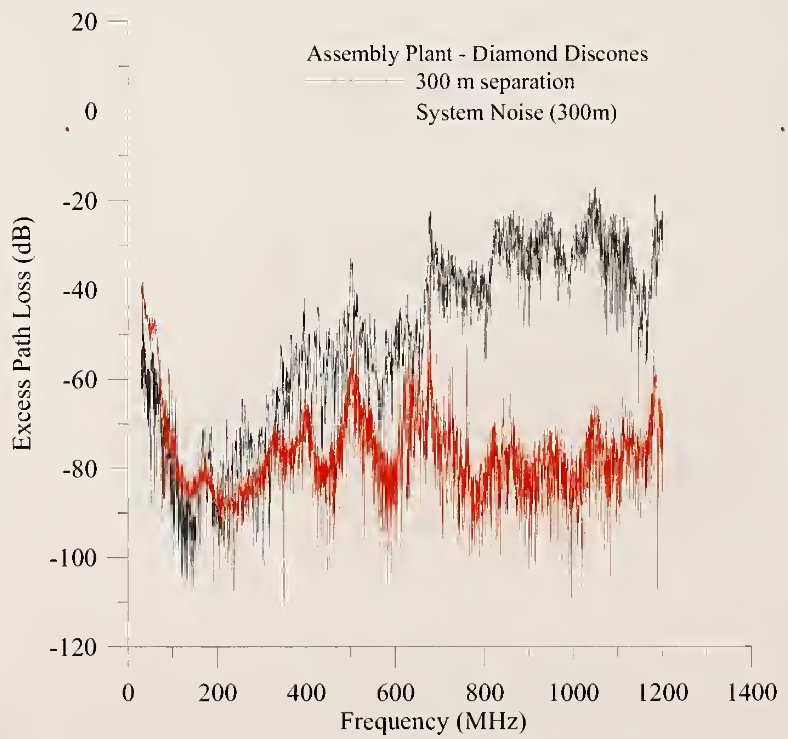
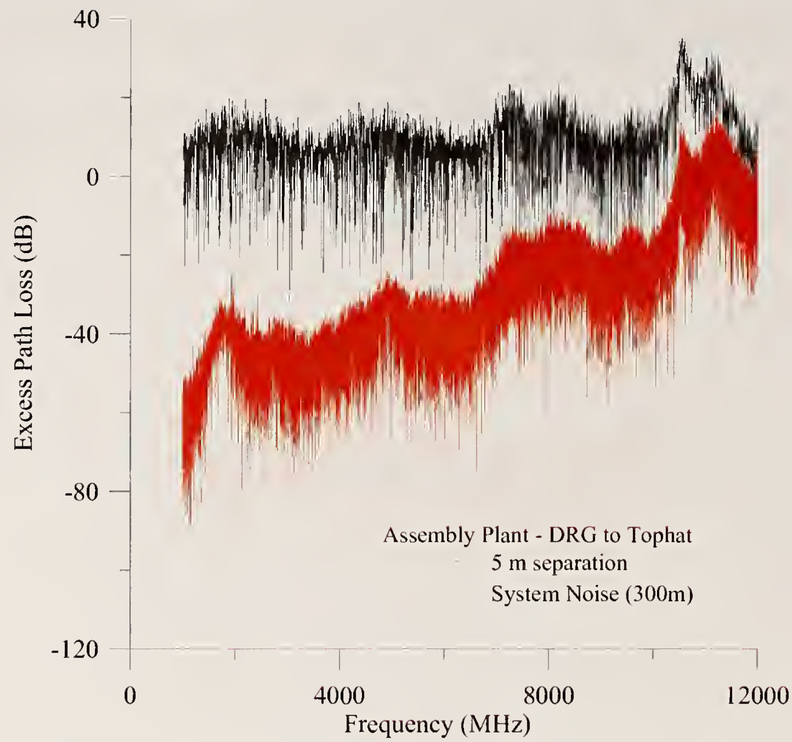


Figure A.7: Excess path loss from 100 MHz to 1.2 GHz in the assembly plant. Top: 275 m separation. Bottom: 300 m separation.

Appendix B: Assembly Plant, High-Frequency Data, Directional Transmit, Omnidirectional Receive Antennas

The following pages contain the complete set of measured data from the assembly plant covering a frequency range of 1 GHz to 12 GHz when directional transmit and omnidirectional receive antennas were used.

Assembly Plant: Directional transmit, omnidirectional receive antennas



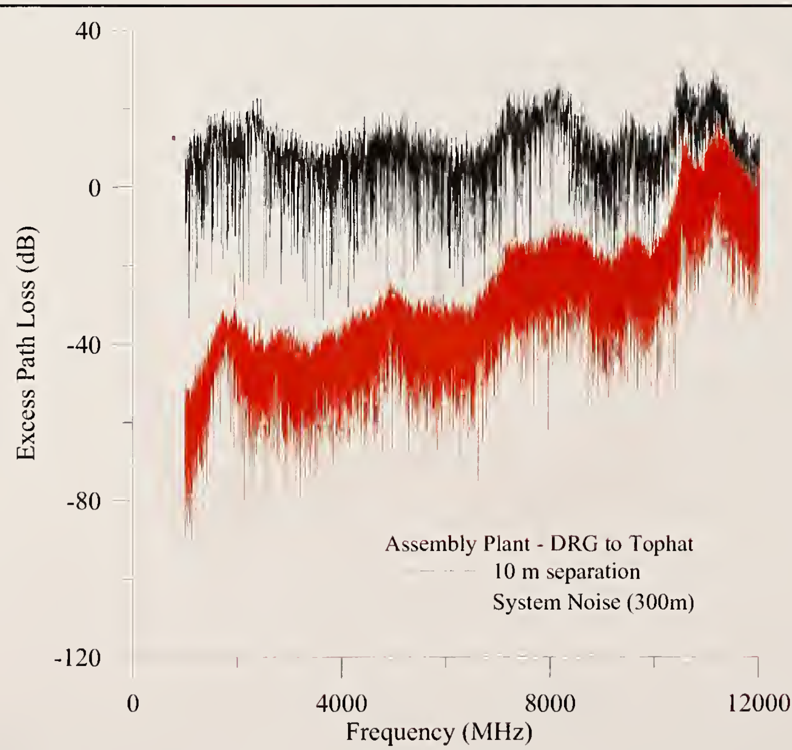


Figure B.1: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 5 m separation. Bottom: 10 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas

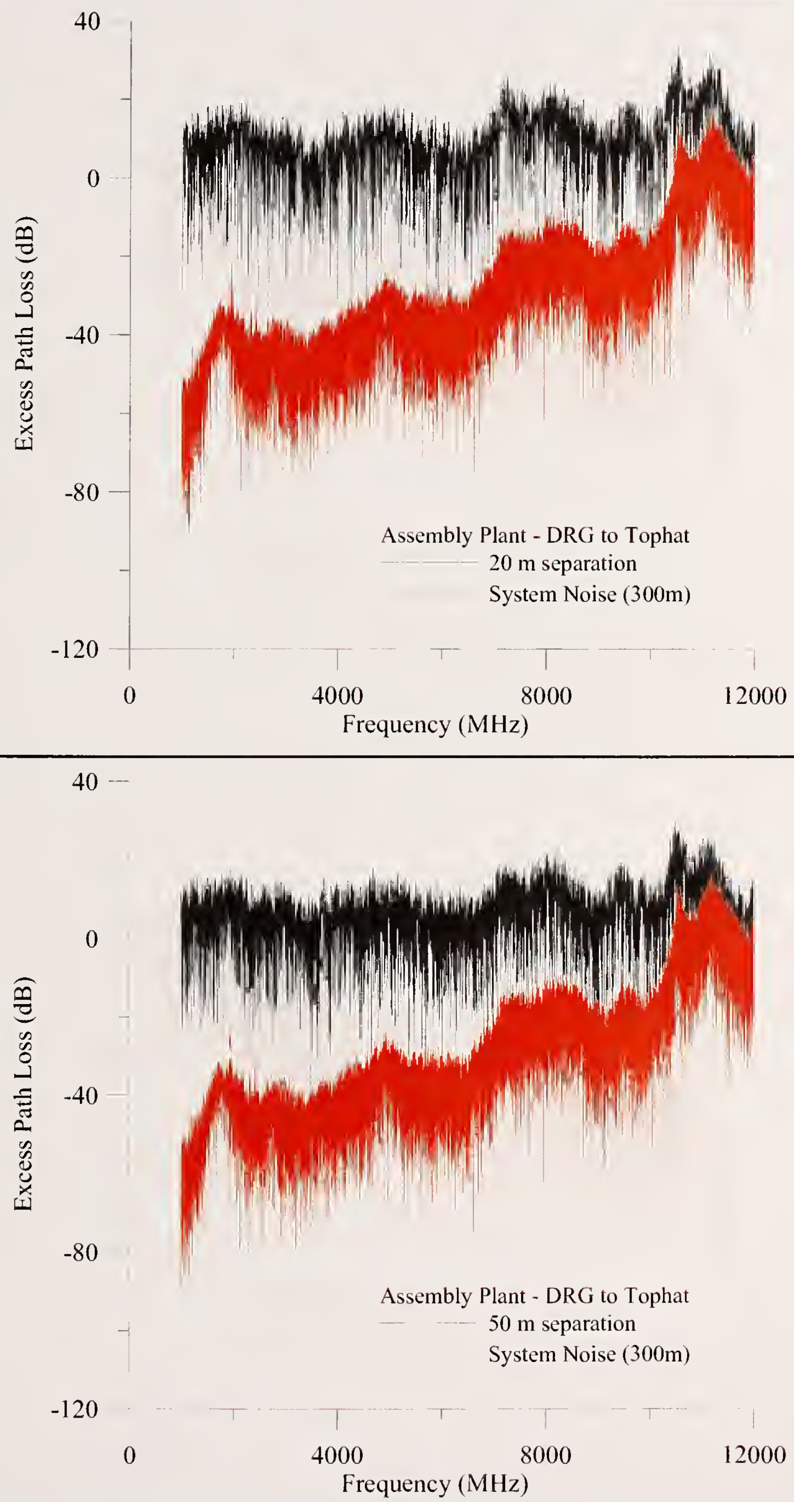


Figure B.2: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 20 m separation. Bottom: 50 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas

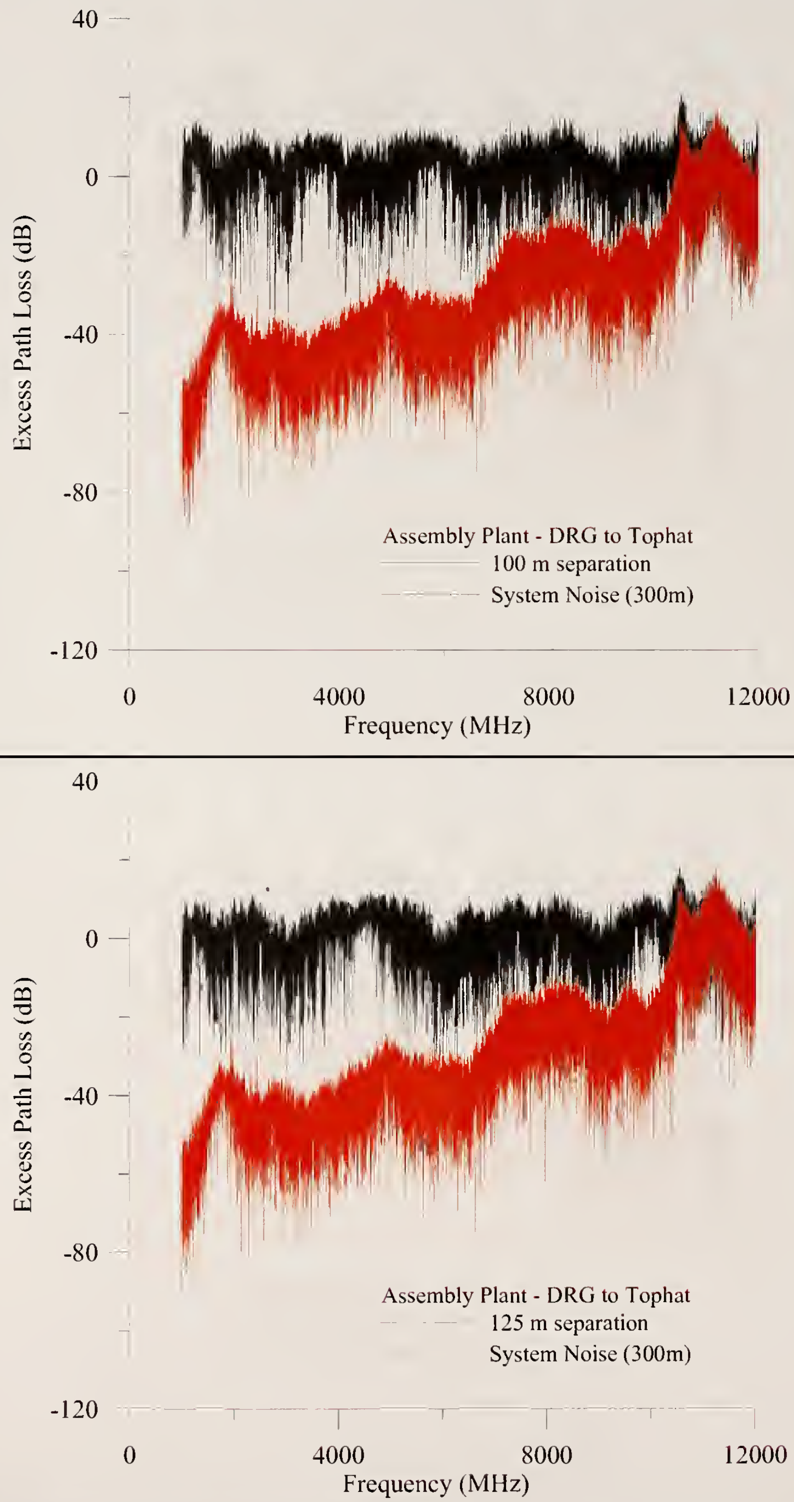
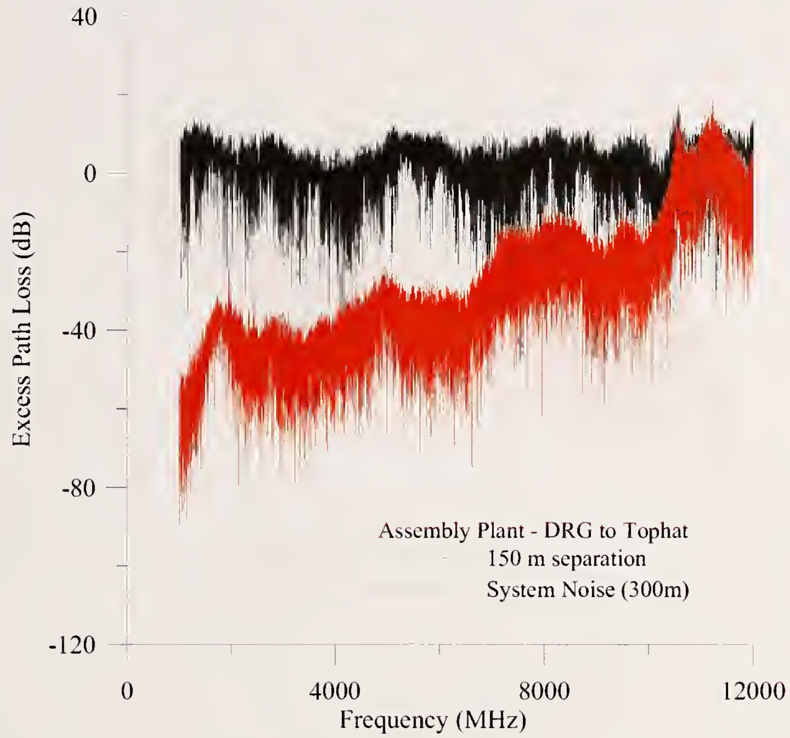


Figure B.3: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 100 m separation. Bottom: 125 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas



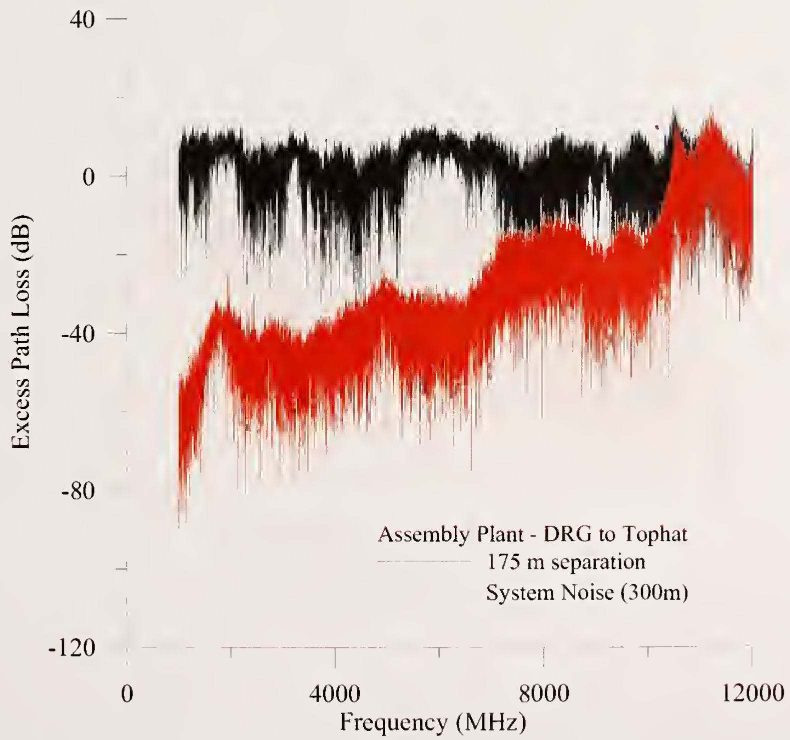
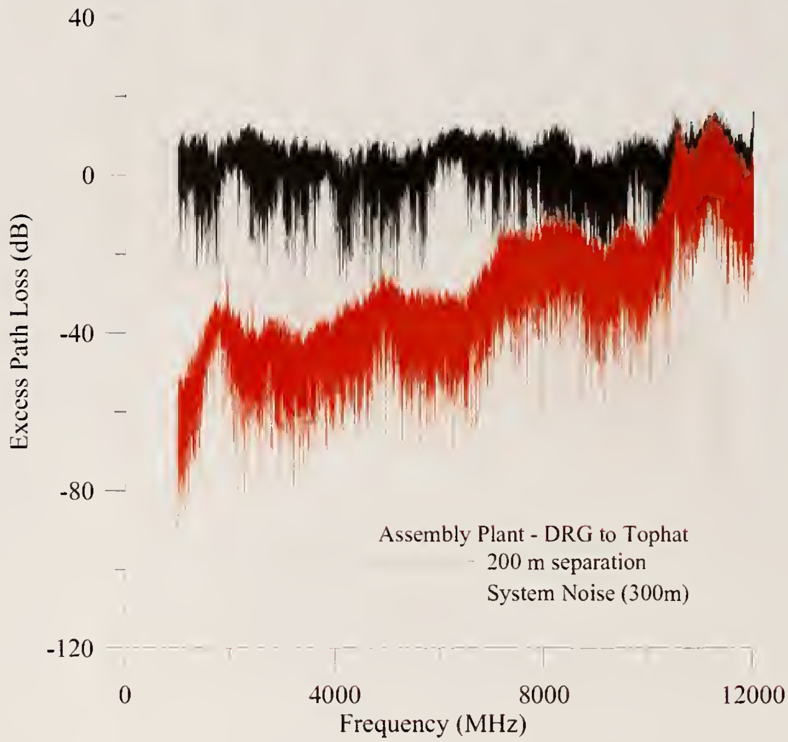


Figure B.4: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 150 m separation. Bottom: 175 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas



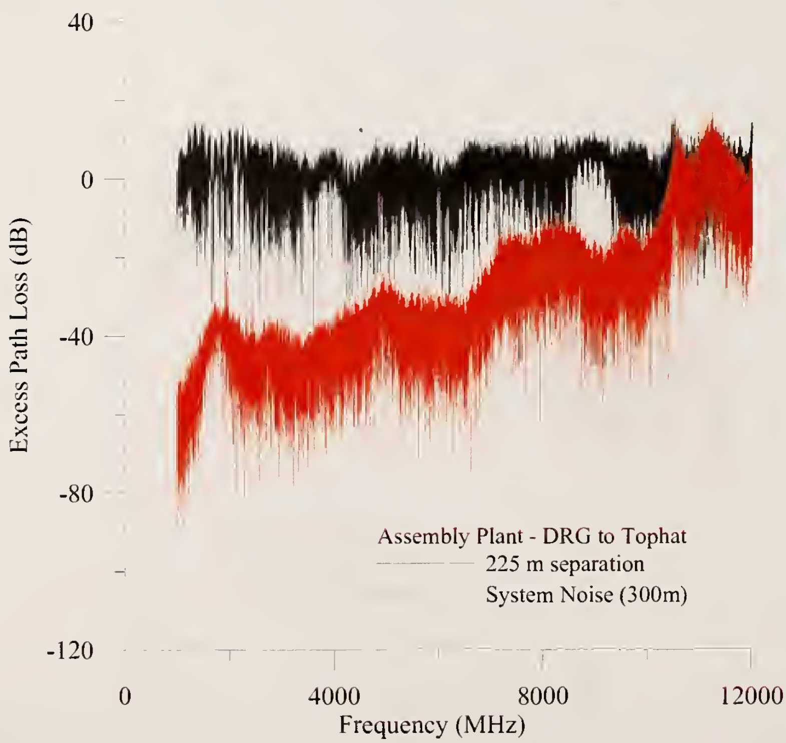
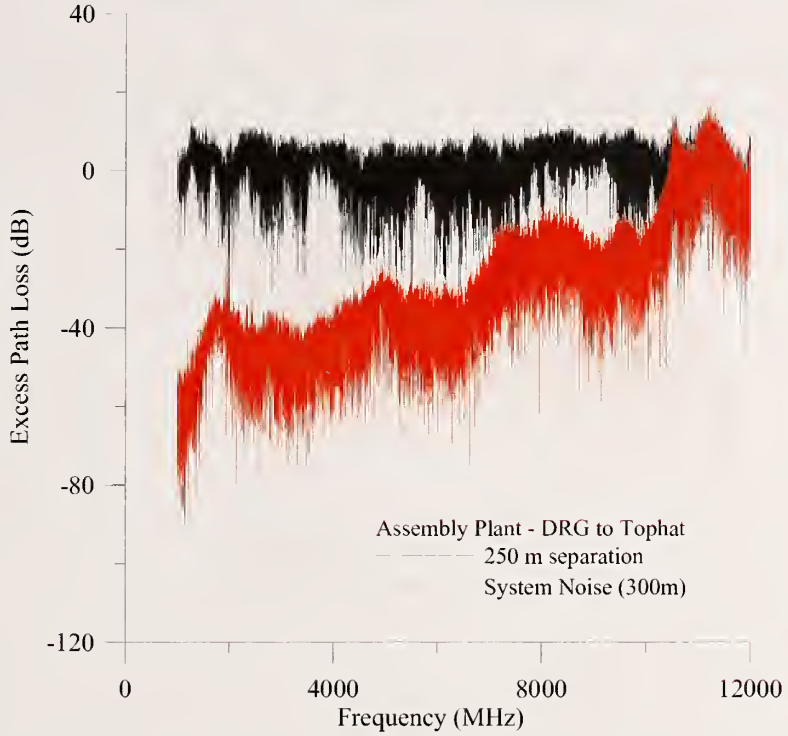


Figure B.5: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 200 m separation. Bottom: 225 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas



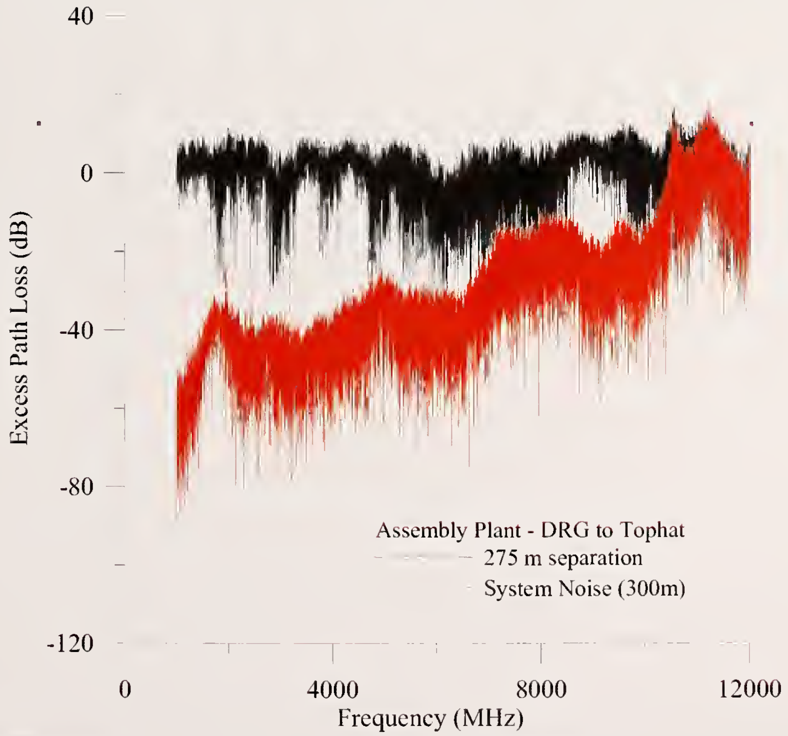


Figure B.6: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 250 m separation. Bottom: 275 m separation.

Assembly Plant: Directional transmit, omnidirectional receive antennas

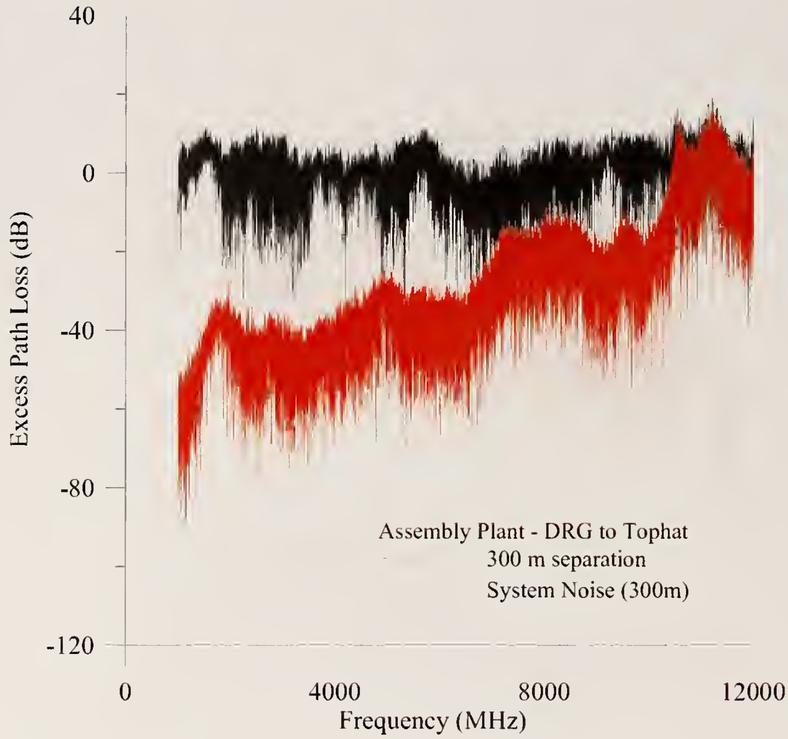
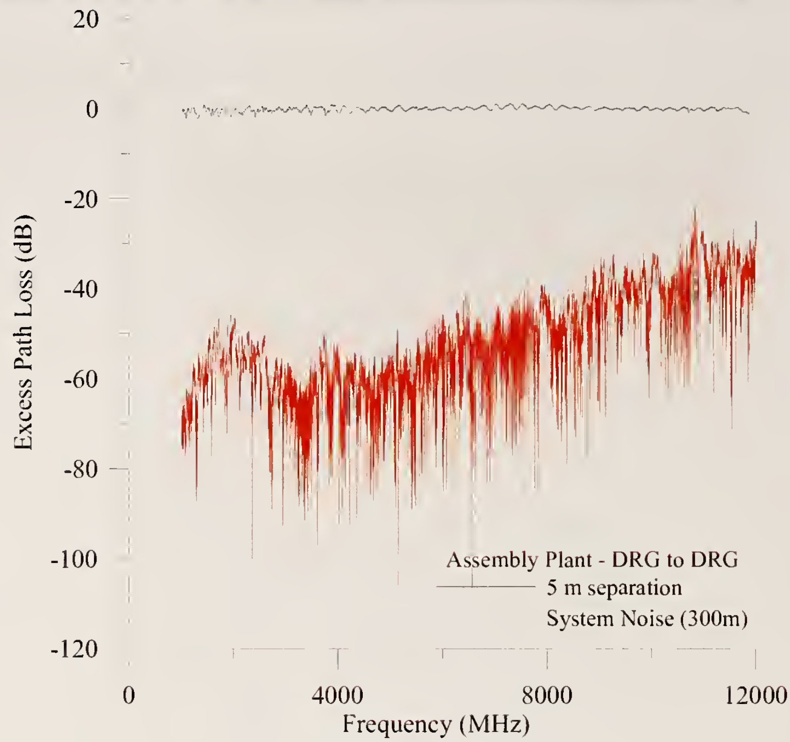


Figure B.7: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 300 m separation.

Appendix C: Assembly Plant, High-Frequency Data, Directional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the assembly plant covering a frequency range of 1 GHz to 12 GHz when directional transmit and receive antennas were used.

Assembly Plant: Directional transmit and receive antennas



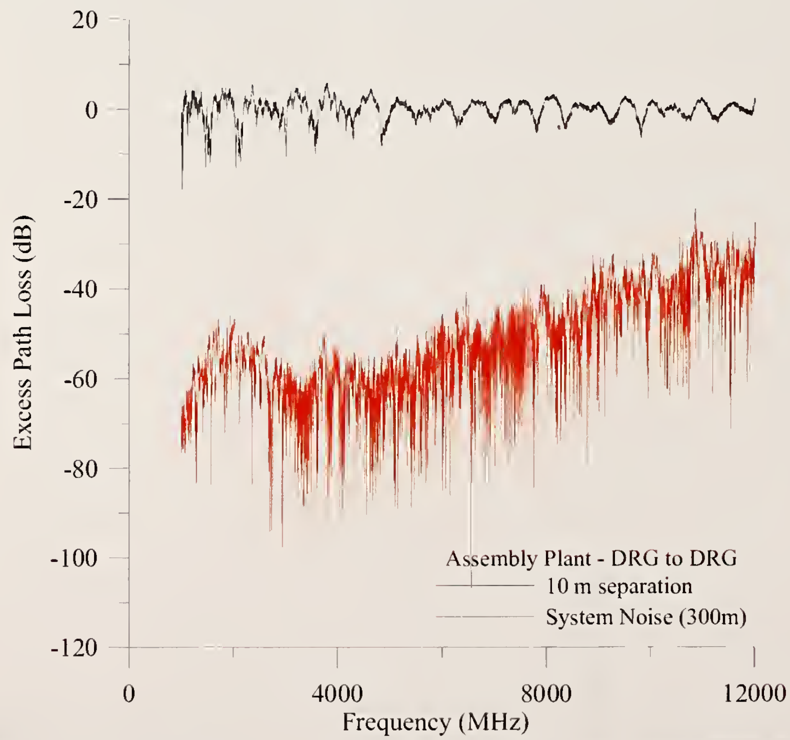


Figure C.1: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 5 m separation. Bottom: 10 m separation.

Assembly Plant: Directional transmit and receive antennas

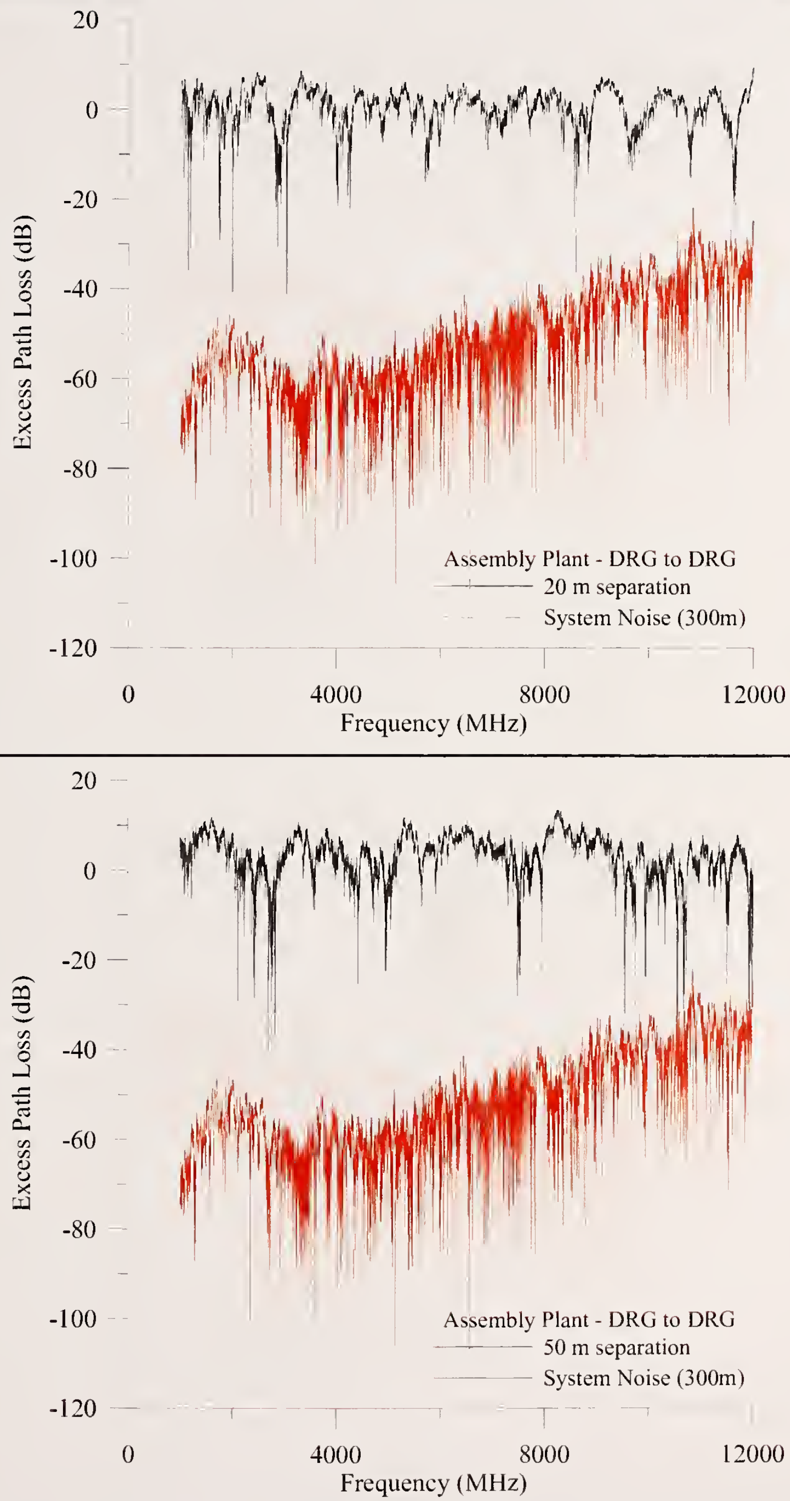
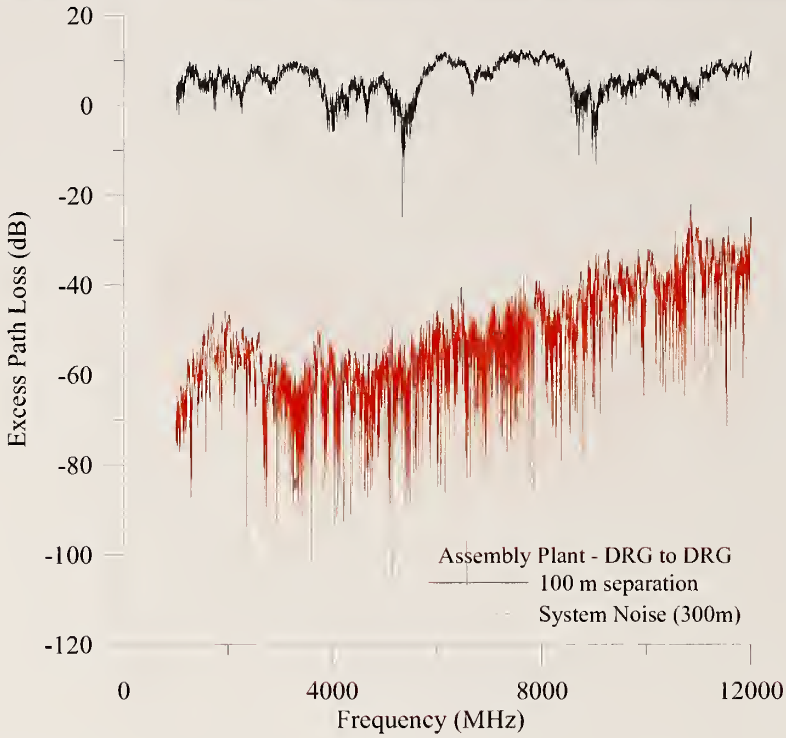


Figure C.2: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 20 m separation. Bottom: 50 m separation.

Assembly Plant: Directional transmit and receive antennas



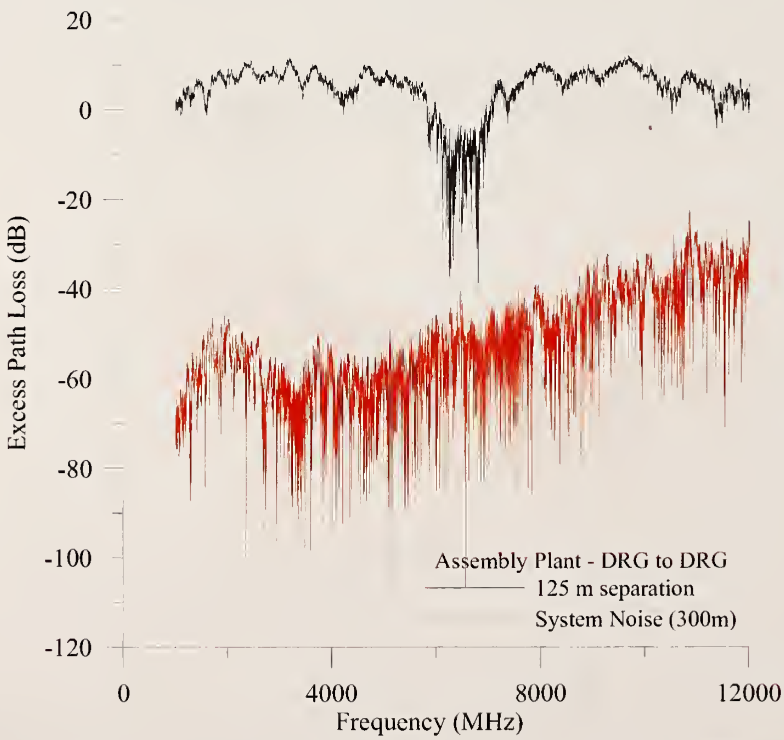
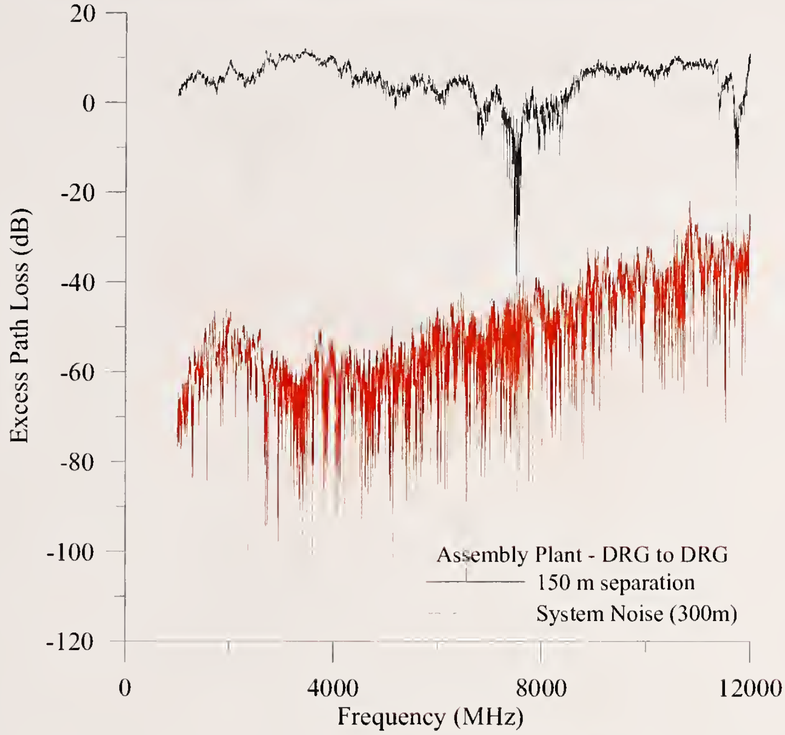


Figure C.3: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 100 m separation. Bottom: 125 m separation.

Assembly Plant: Directional transmit and receive antennas



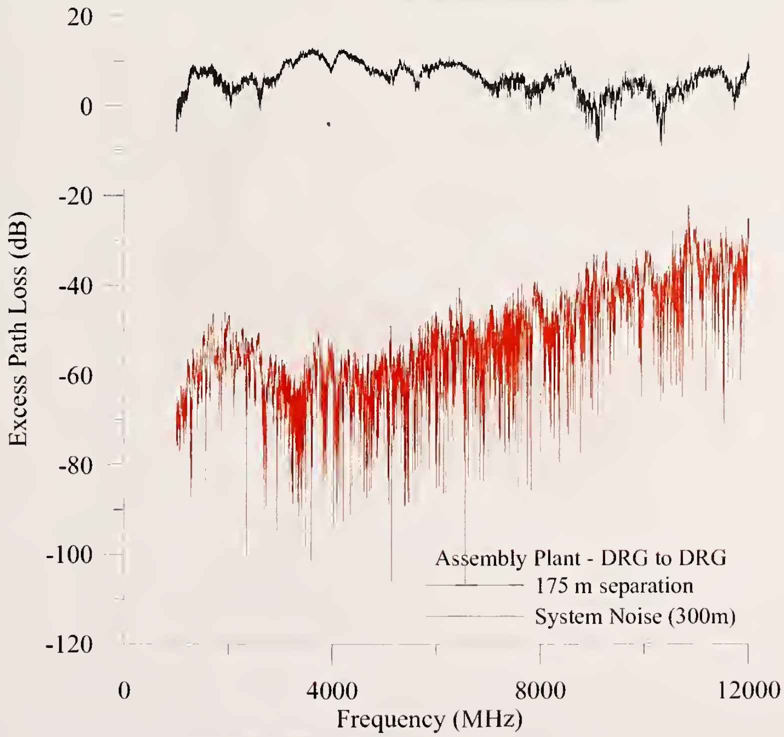
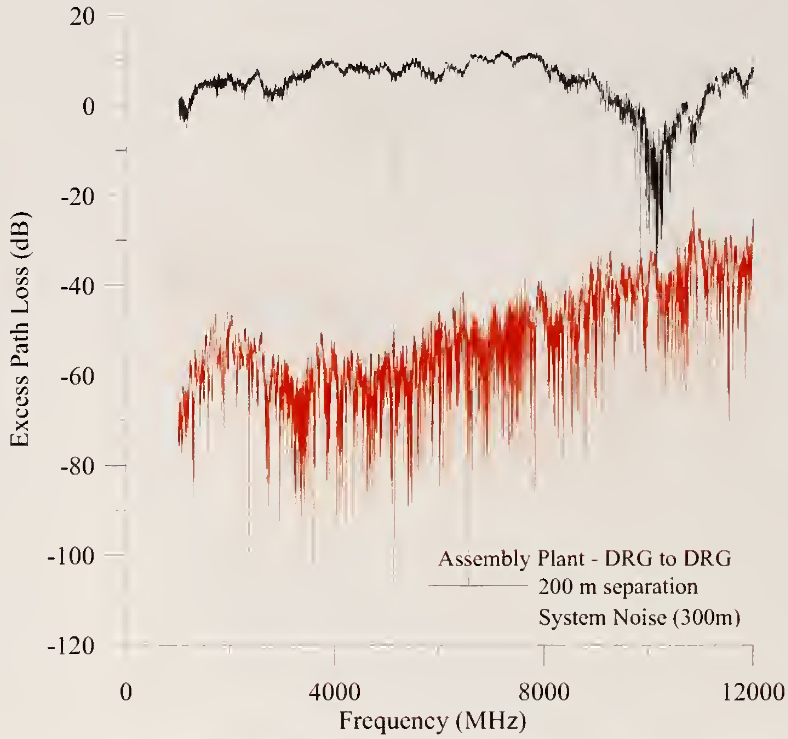


Figure C.4: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 150 m separation. Bottom: 175 m separation.

Assembly Plant: Directional transmit and receive antennas



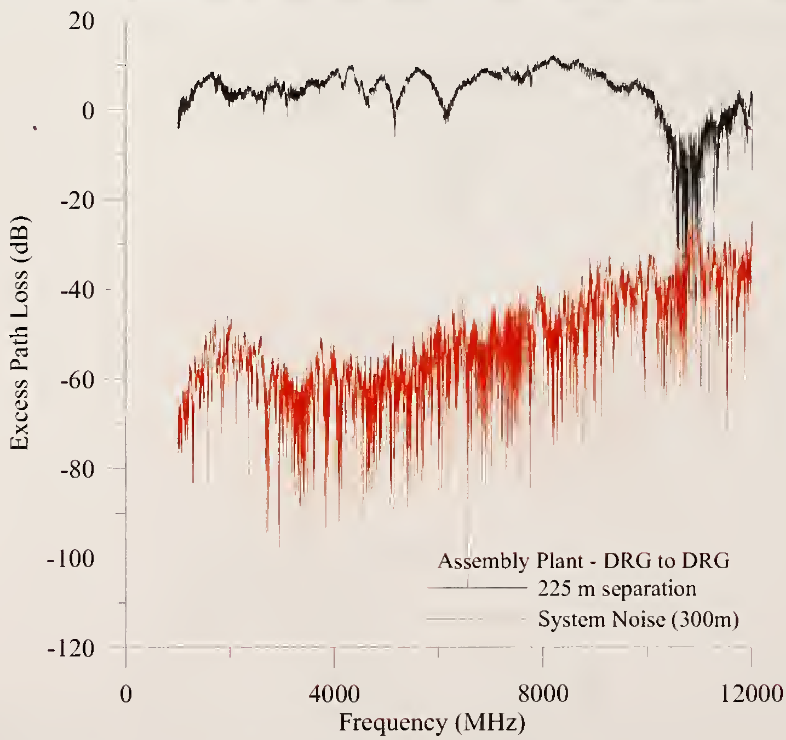


Figure C.5: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 200 m separation. Bottom: 225 m separation.

Assembly Plant: Directional transmit and receive antennas

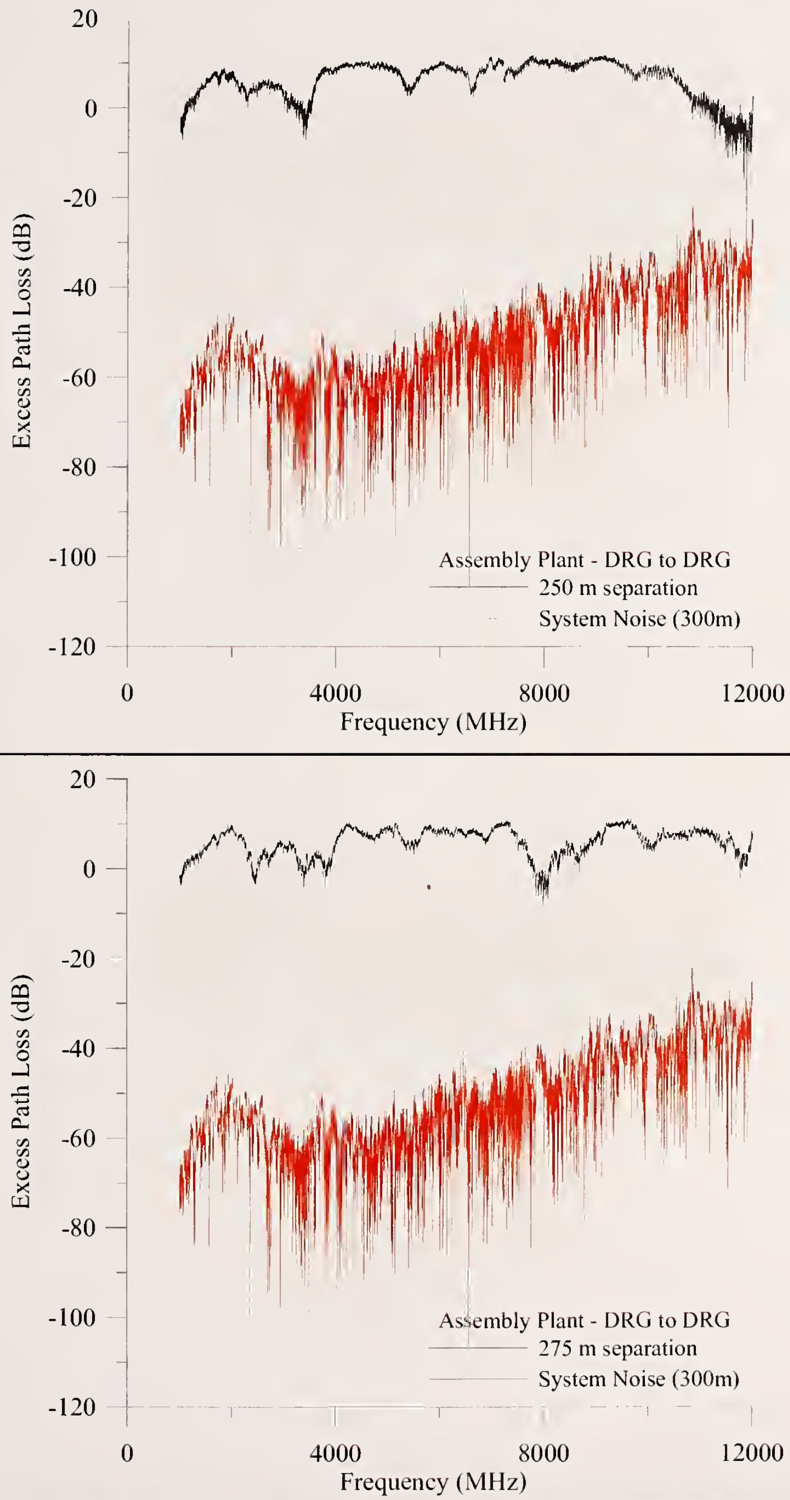


Figure C.6: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 250 m separation. Bottom: 275 m separation.

Assembly Plant: Directional transmit and receive antennas

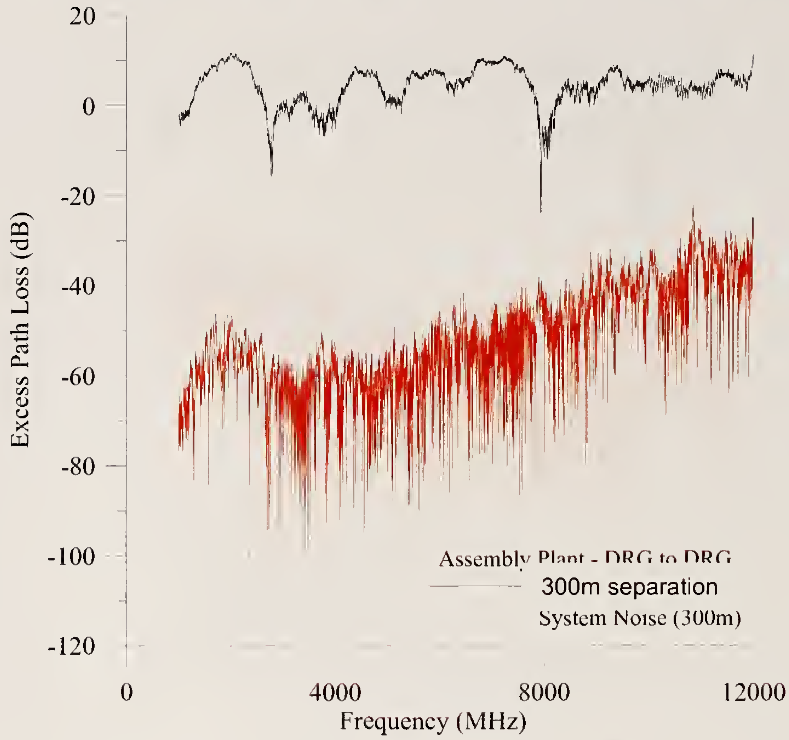
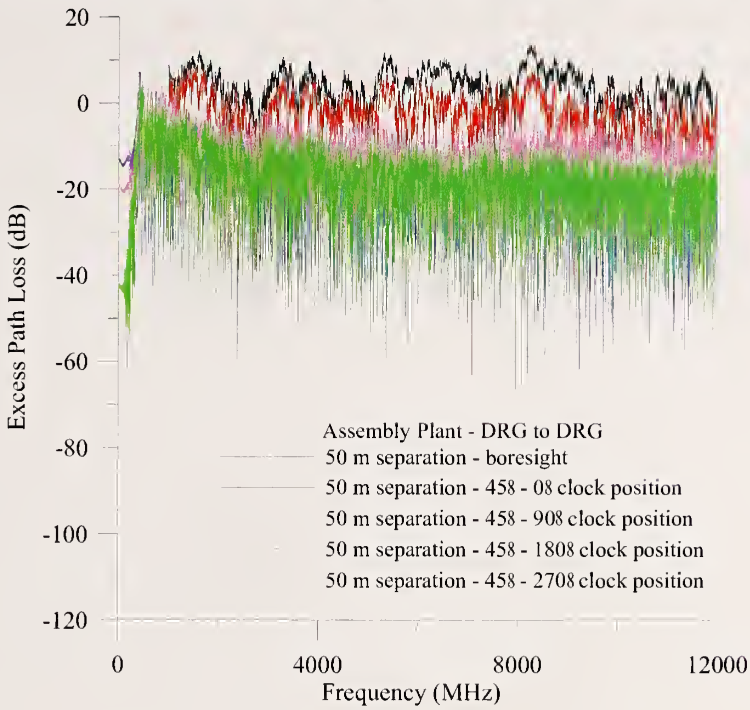


Figure C.7: Excess path loss from 1 GHz to 12 GHz in the assembly plant. Top: 300 m separation.

Assembly Plant: Directional transmit and receive antennas



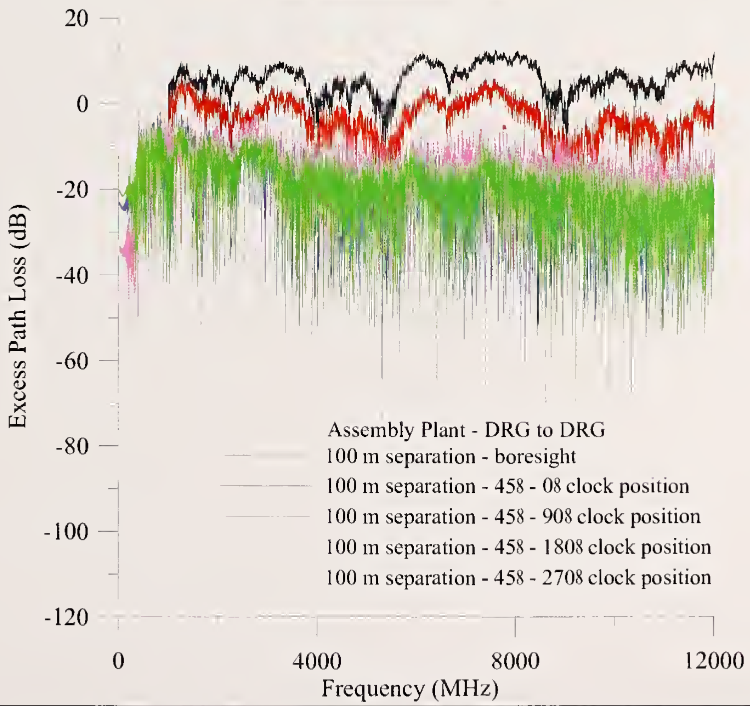


Figure C.8: Excess path loss from 1 GHz to 12 GHz in the assembly plant when the receive antenna is rotated through angles from zero (boresight) to 270° as defined in Figure 5-3 for the stamping plant. Top: 50 m separation. Bottom: 100 m separation.

Assembly Plant: Directional transmit and receive antennas

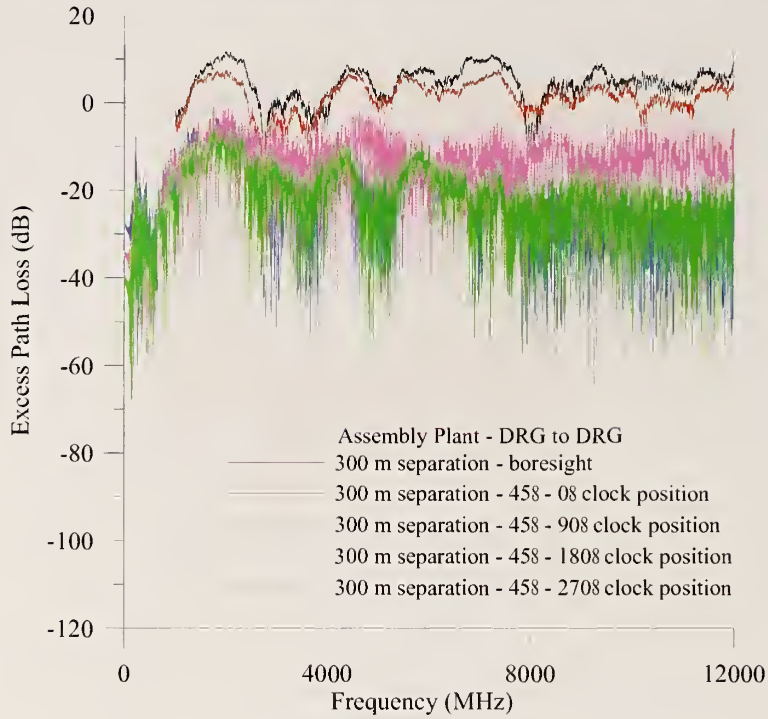
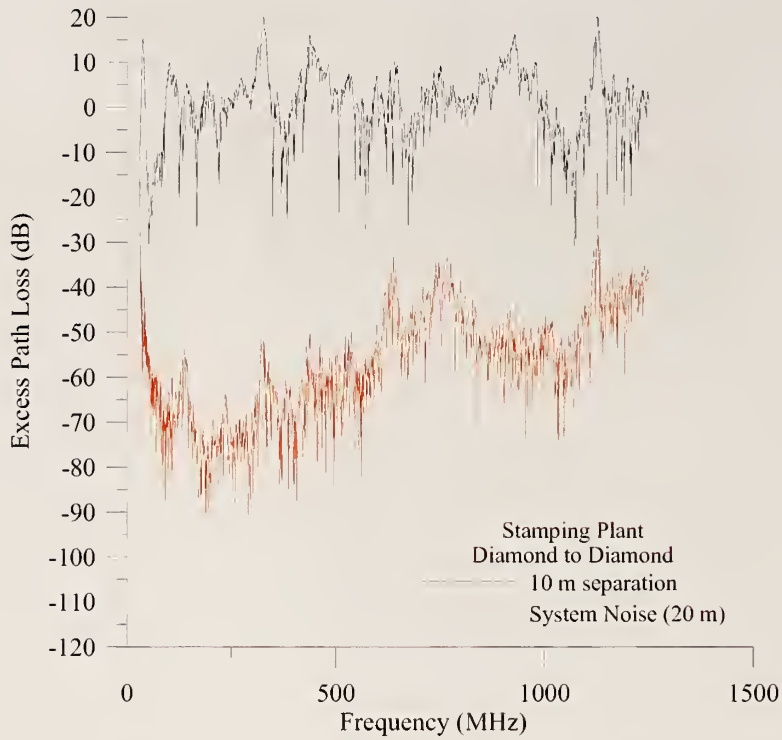


Figure C.9: Excess path loss from 1 GHz to 12 GHz in the assembly plant when the receive antenna is rotated through angles from zero (boresight) to 270° as defined in Figure 5-3 for the stamping plant. Top: 300 m separation.

Appendix D: Stamping Plant, Low-Frequency Data, Omnidirectional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the stamping plant covering a frequency range of 100 MHz to 1.2 GHz when omnidirectional transmit and receive antennas were used.

Metal Stamping Plant: Omnidirectional antennas



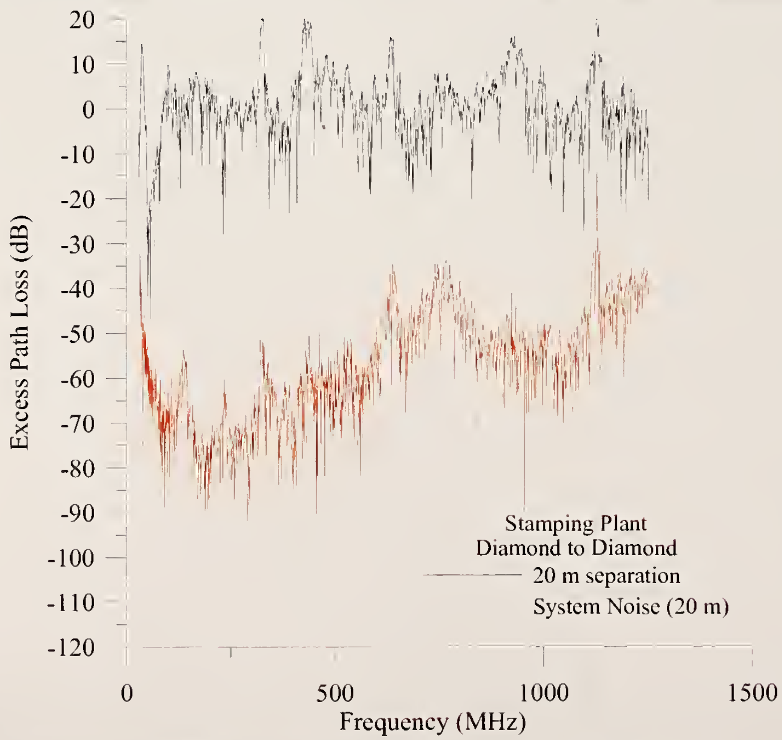
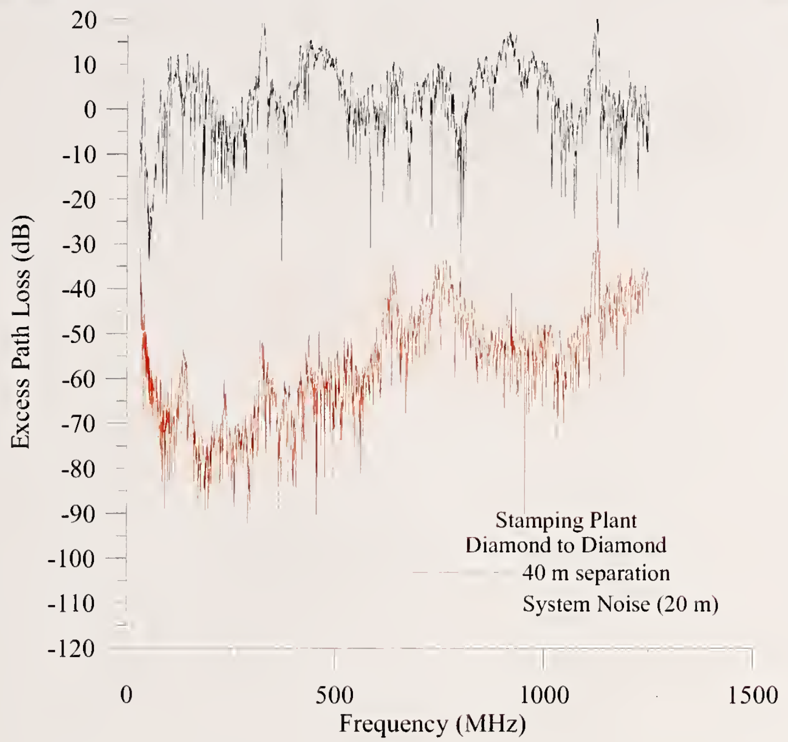


Figure D.1: Excess path loss from 100 MHz to 1.2 GHz in the stamping plant. Top: 10 m separation. Bottom: 20 m separation.

Metal Stamping Plant: Omnidirectional antennas



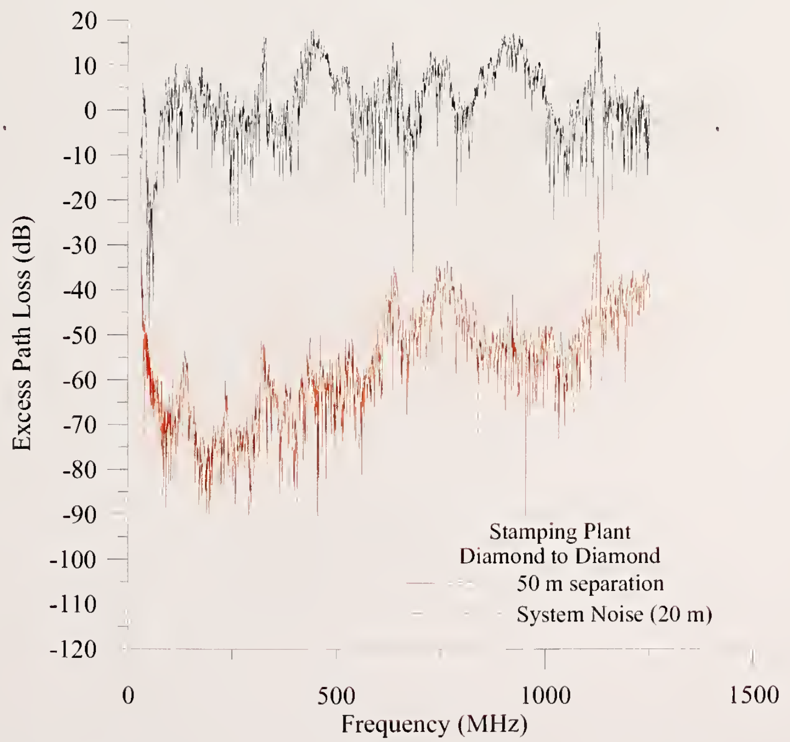
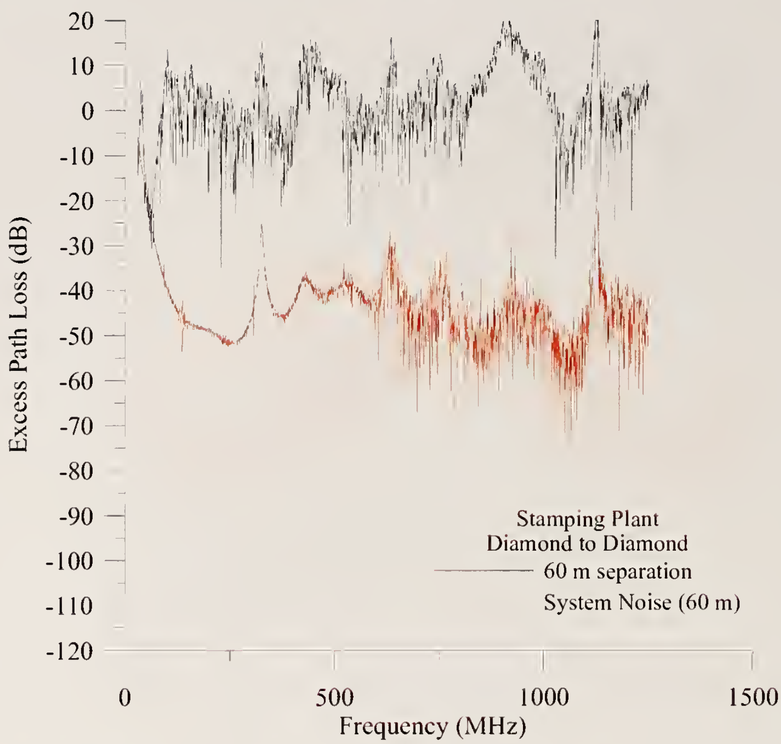


Figure D.2: Excess path loss from 100 MHz to 1.2 GHz in the stamping plant. Top: 40 m separation. Bottom: 50 m separation.

Metal Stamping Plant: Omnidirectional antennas



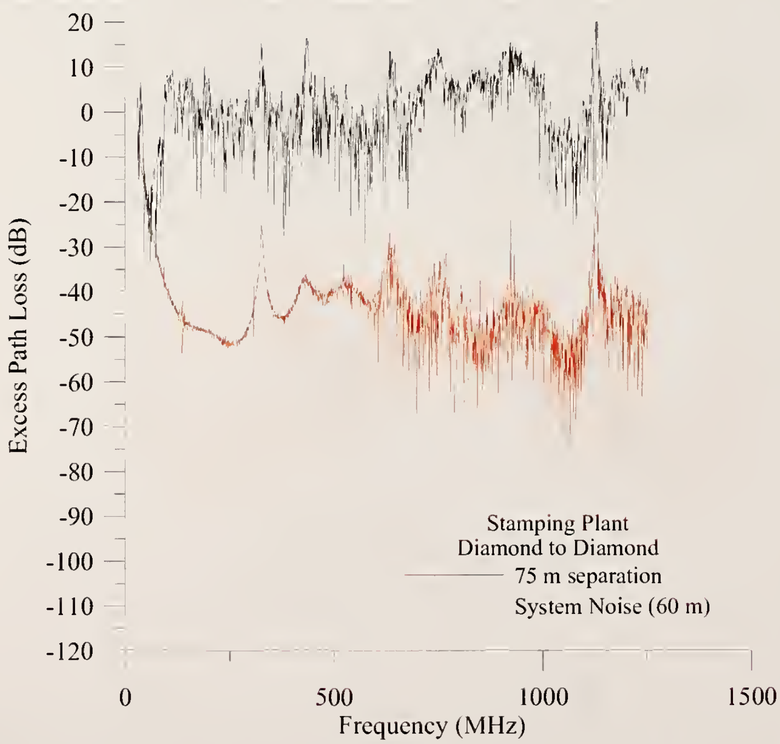
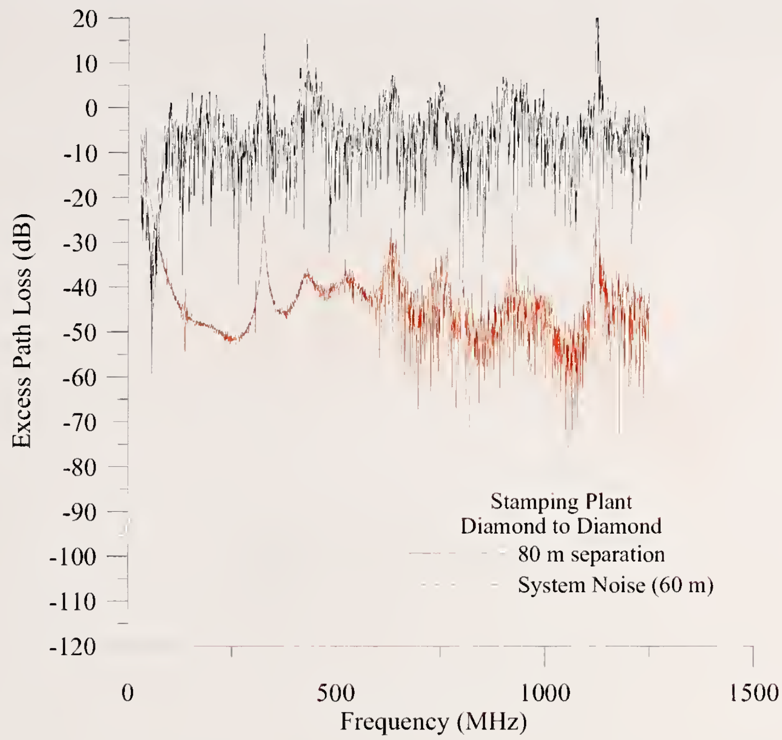


Figure D.3: Excess path loss from 100 MHz to 1.2 GHz in the stamping plant. Top: 60 m separation. Bottom: 75 m separation.

Metal Stamping Plant: Omnidirectional antennas



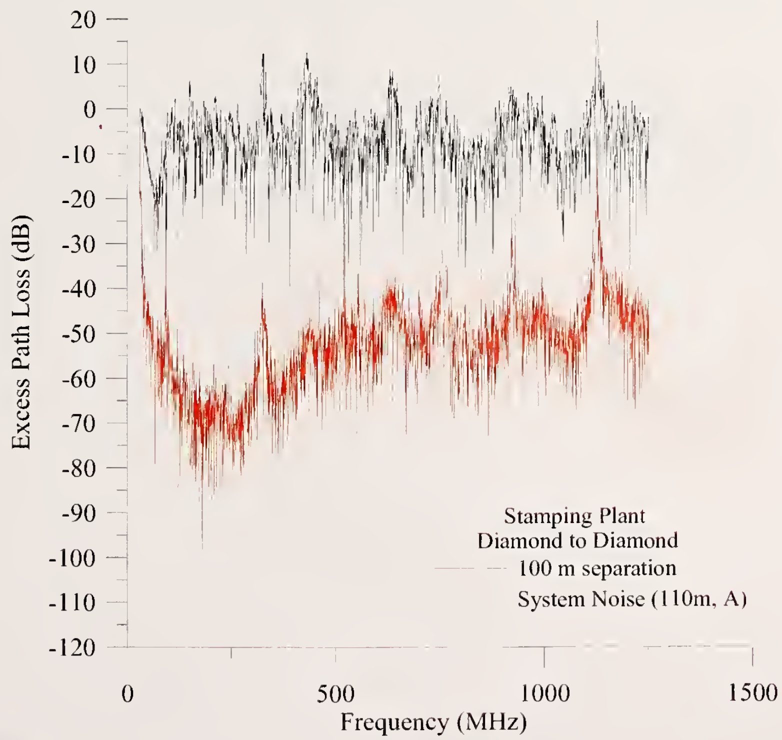
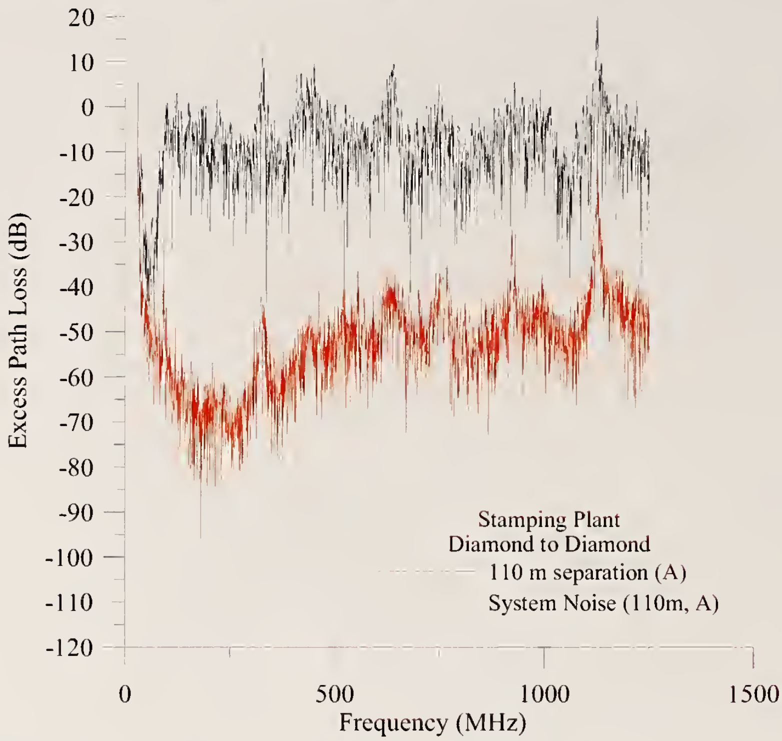


Figure D.4: Excess path loss from 100 MHz to 1.2 GHz in the stamping plant. Top: 80 m separation. Bottom: 100 m separation.

Metal Stamping Plant: Omnidirectional antennas



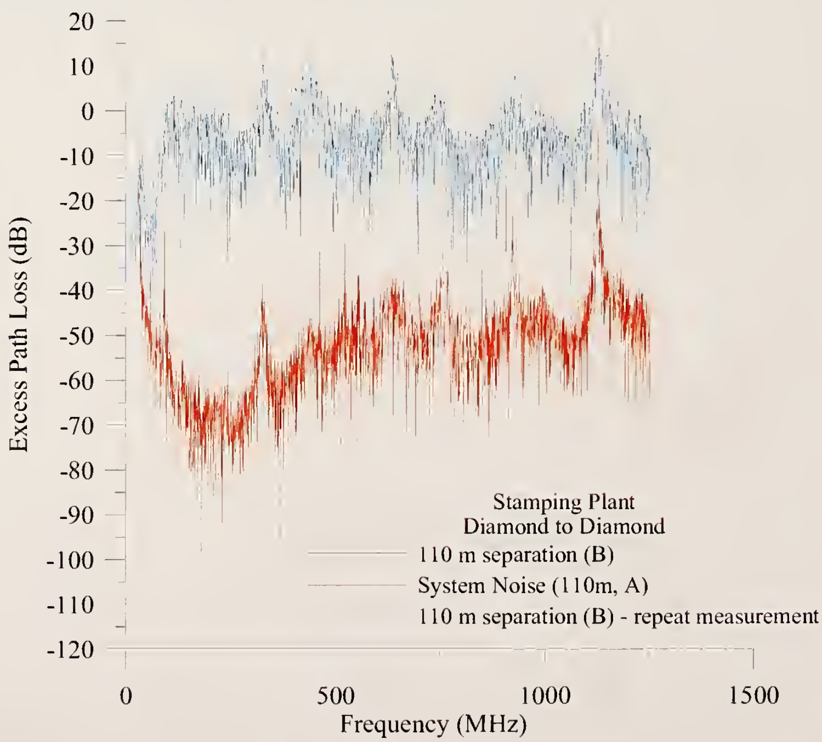
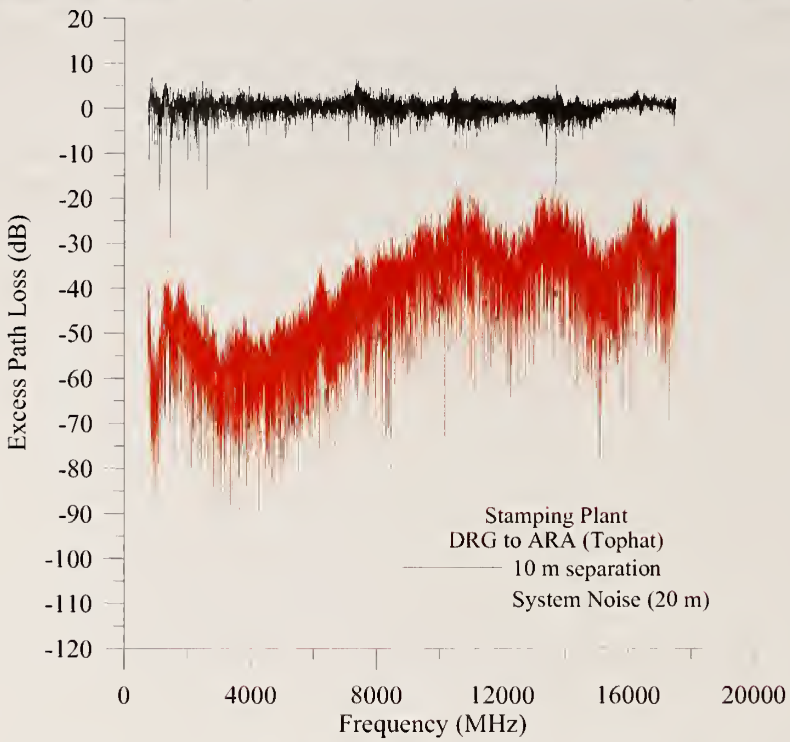


Figure D.5: Excess path loss from 100 MHz to 1.2 GHz in the stamping plant. Top: 110 m separation, straight path. Bottom: 110 m separation, around corner. See Figure 5.3

Appendix E: Metal Stamping Plant, High-Frequency Data, Directional Transmit, Omnidirectional Receive Antennas

The following pages contain the complete set of measured data from the metal stamping plant covering a frequency range of 1 GHz to 12 GHz when directional transmit and omnidirectional receive antennas were used.

Stamping Plant: Directional transmit, omnidirectional receive antennas



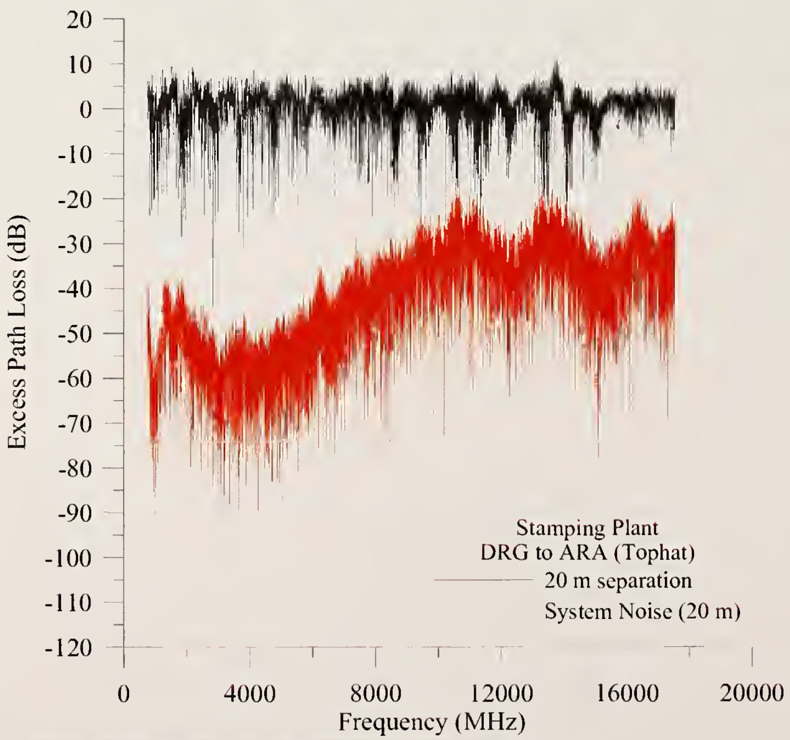


Figure E.1: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 10 m separation. Bottom: 20 m separation.

Stamping Plant: Directional transmit, omnidirectional receive antennas

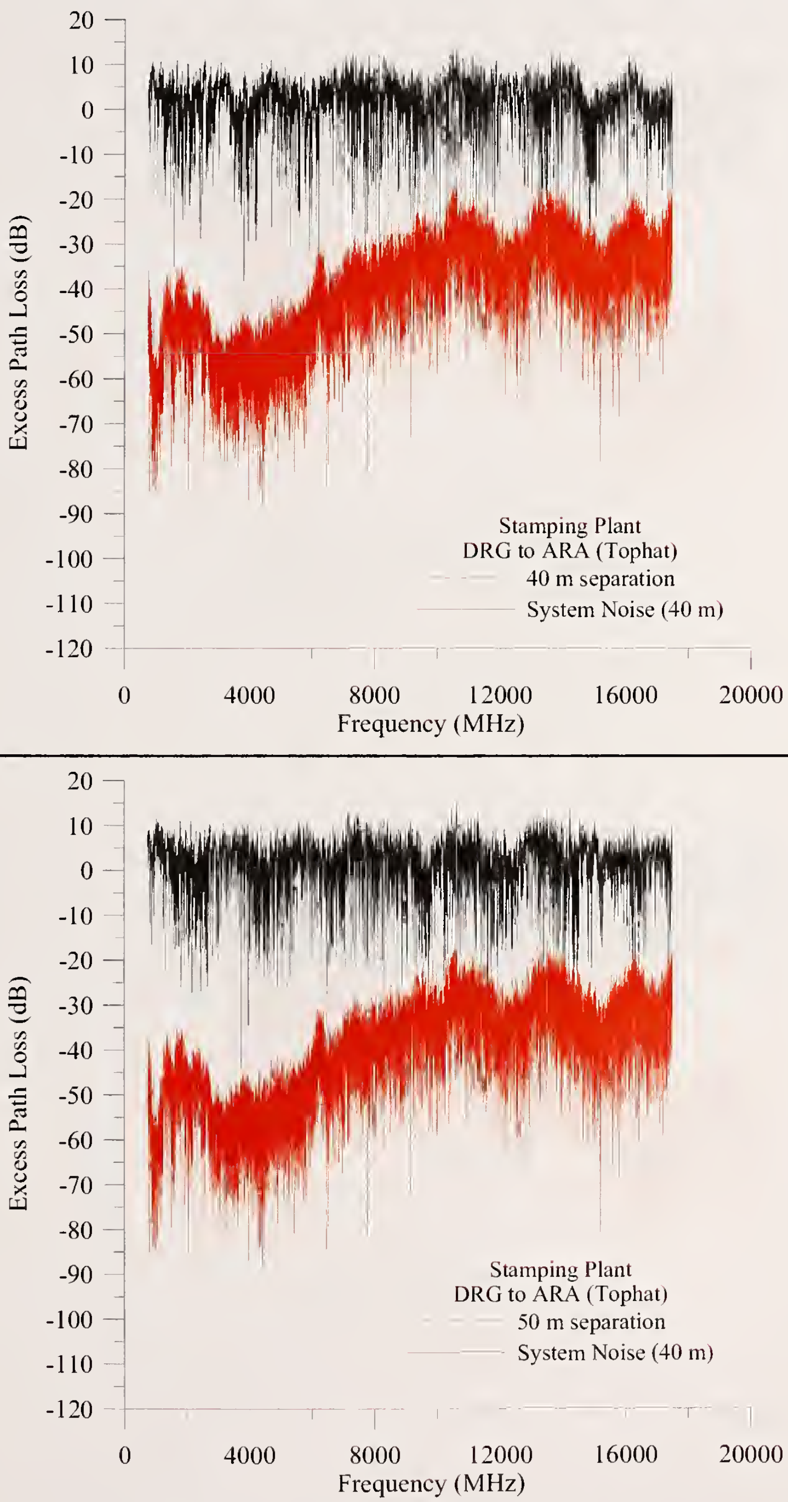
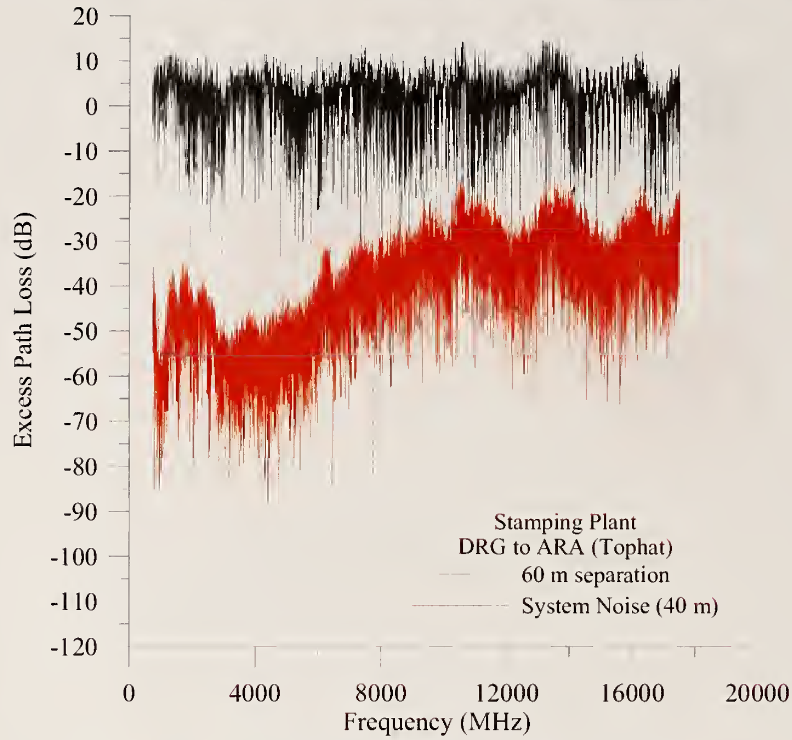


Figure E.2: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 40 m separation. Bottom: 50 m separation.

Stamping Plant: Directional transmit, omnidirectional receive antennas



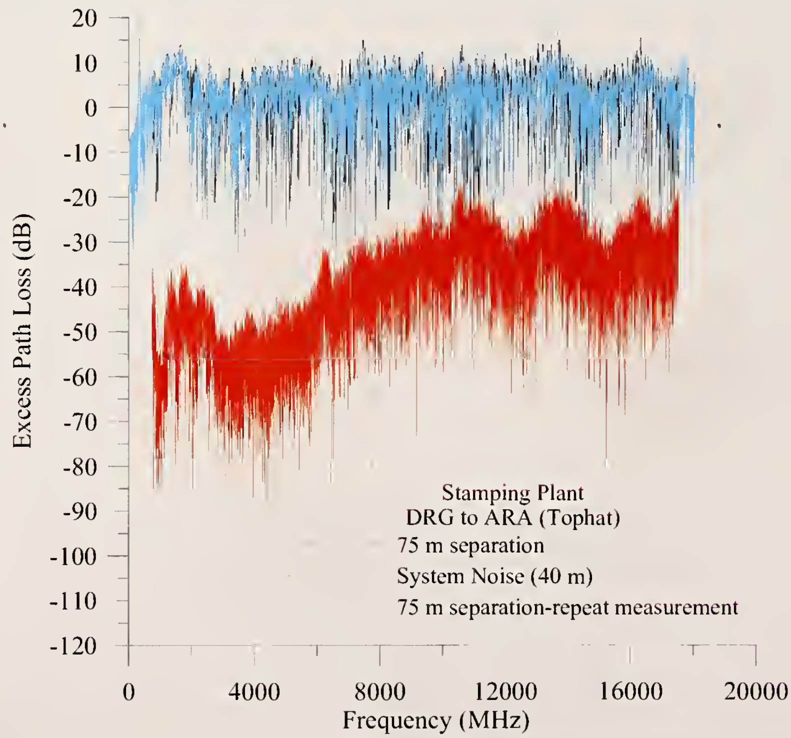
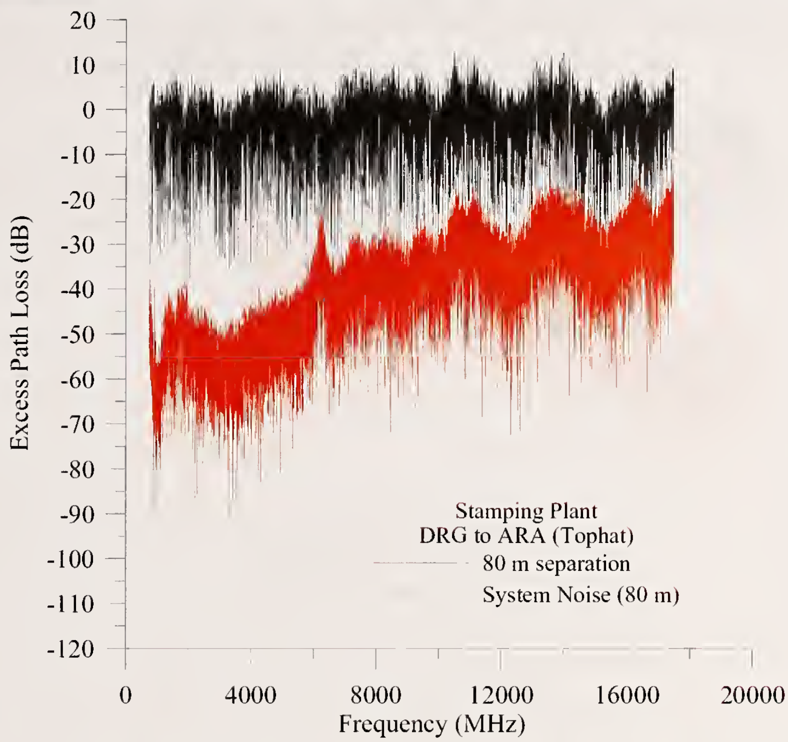


Figure E.3: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 60 m separation. Bottom: 75 m separation.

Stamping Plant: Directional transmit, omnidirectional receive antennas



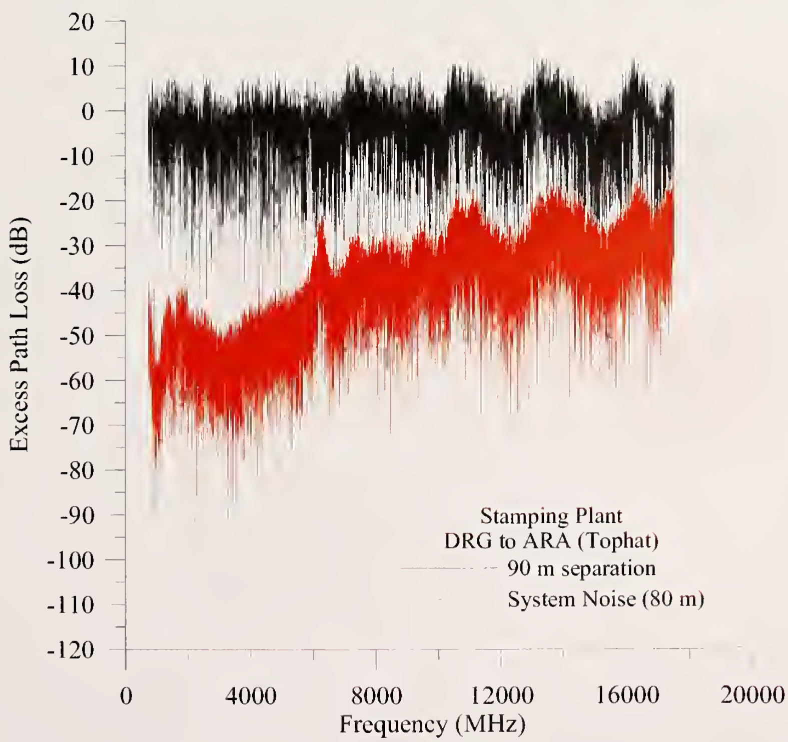
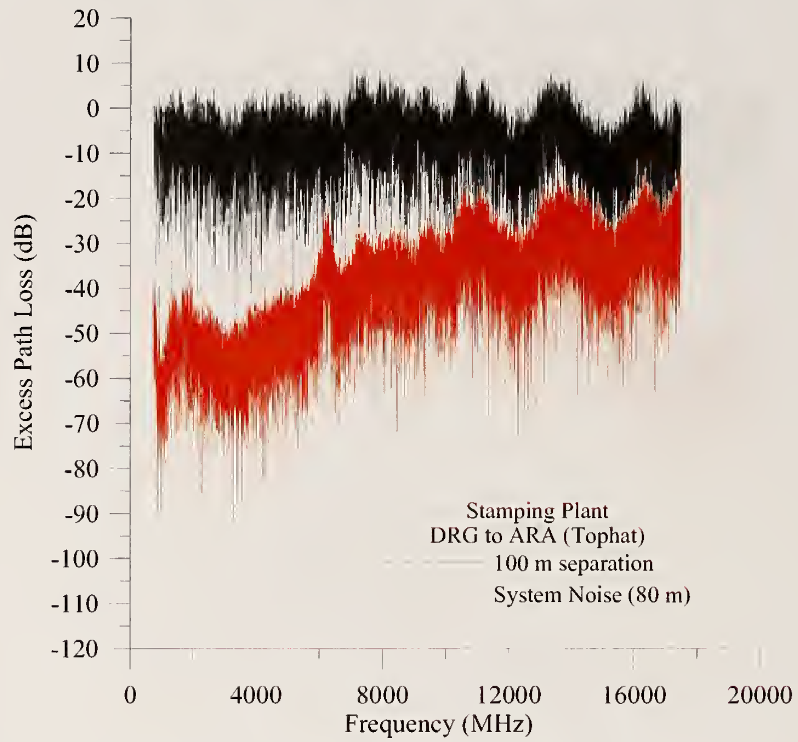


Figure E.4: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 80 m separation. Bottom: 90 m separation.

Stamping Plant: Directional transmit, omnidirectional receive antennas



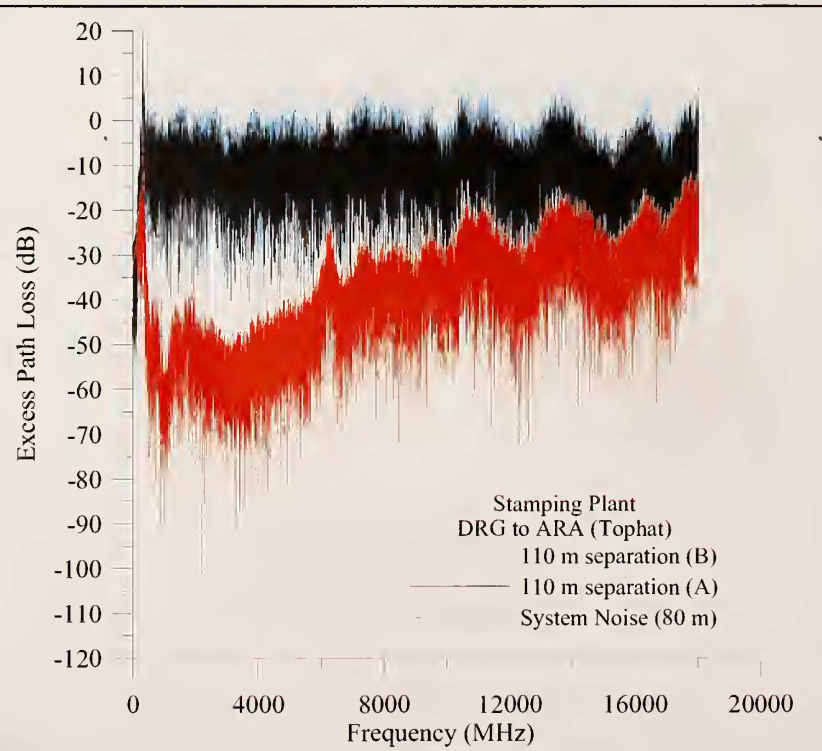


Figure E.5: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 100 m separation. Bottom: 110 m separation, see Figure 5-3.

Appendix F: Metal Stamping Plant, High-Frequency Data, Directional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the metal stamping plant covering a frequency range of 1 GHz to 12 GHz when directional transmit and receive antennas were used.

Stamping Plant: Directional transmit, receive antennas

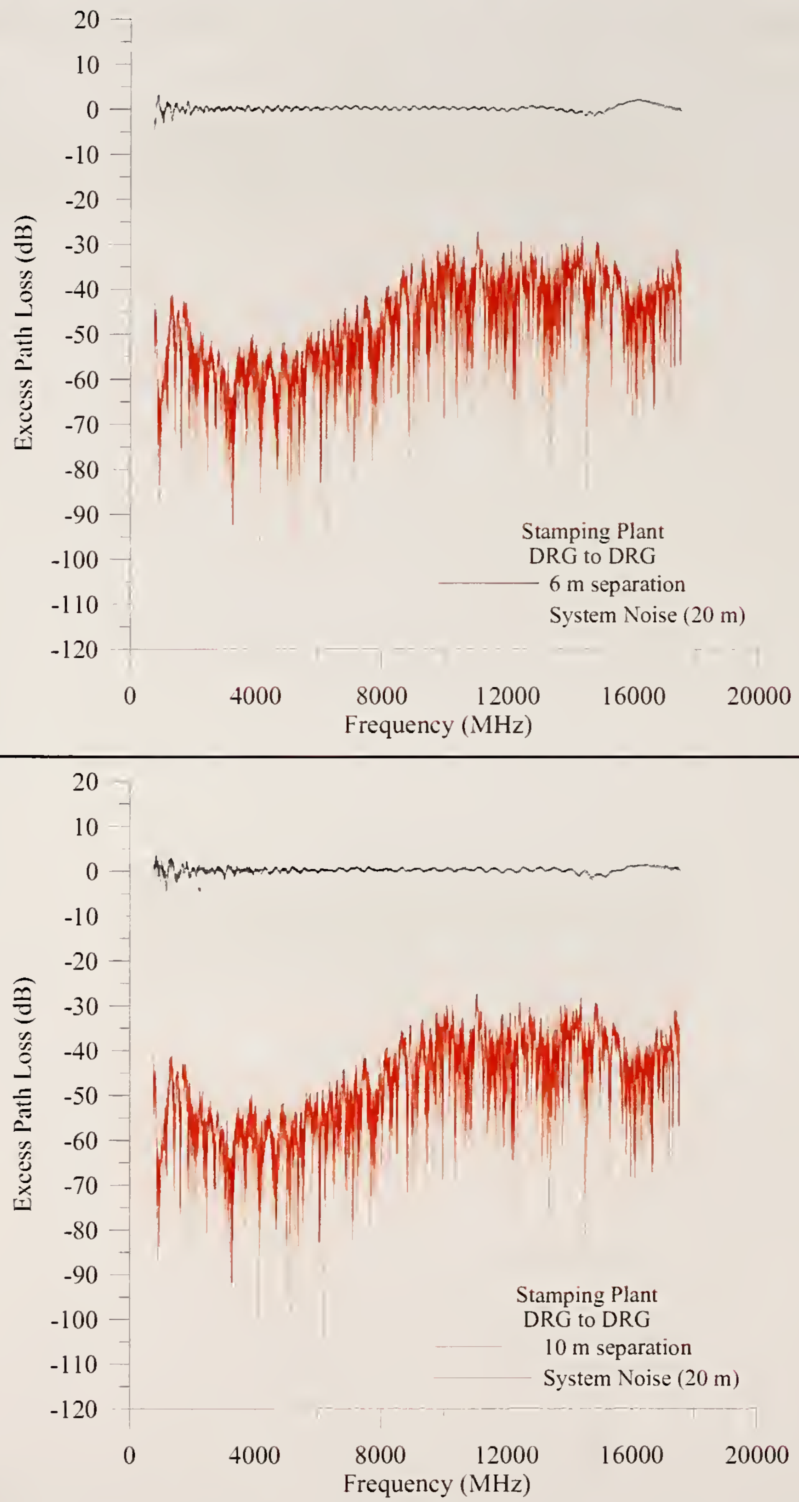
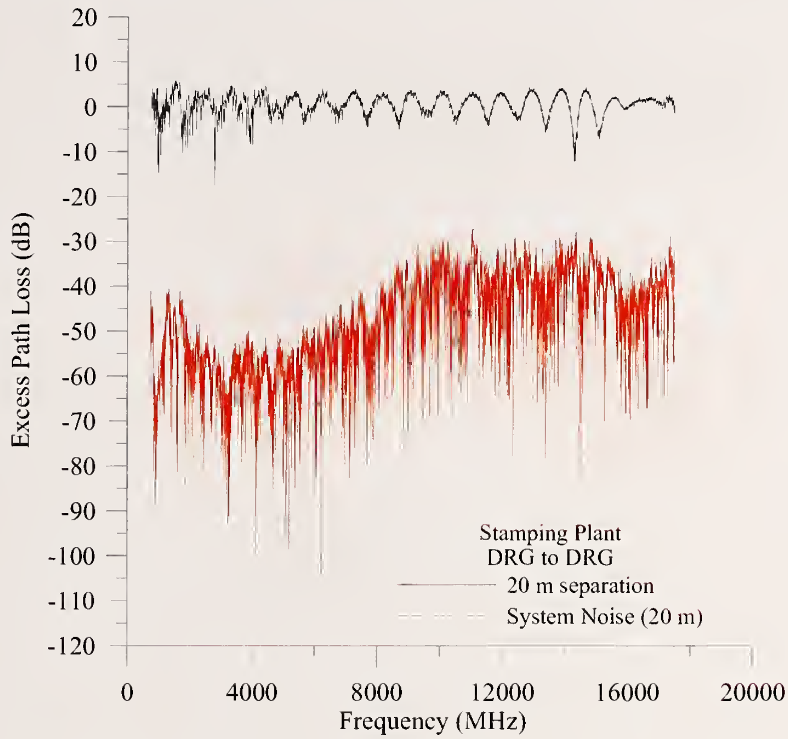


Figure F.1: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 6 m separation. Bottom: 10 m separation.

Stamping Plant: Directional transmit, receive antennas



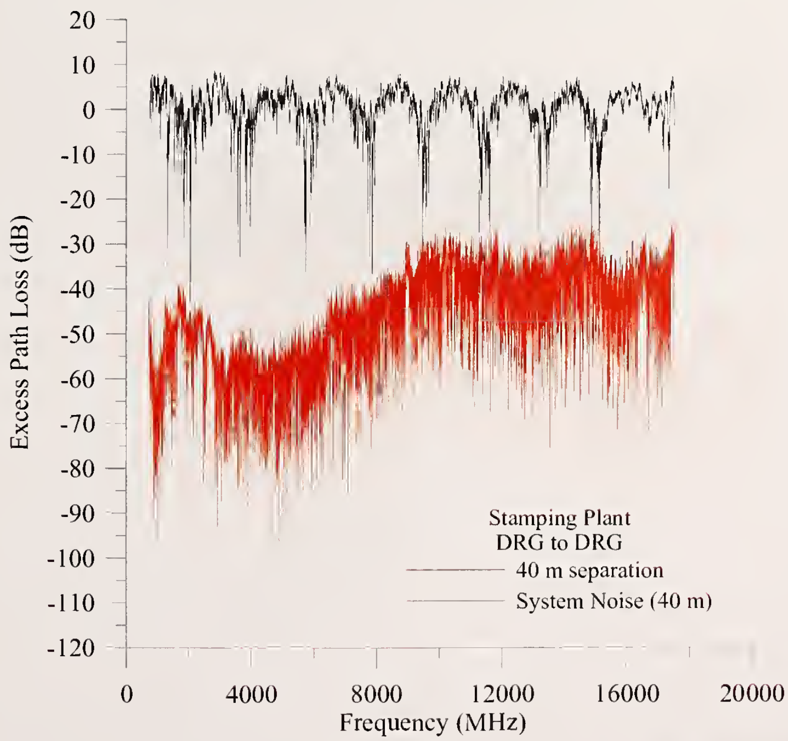
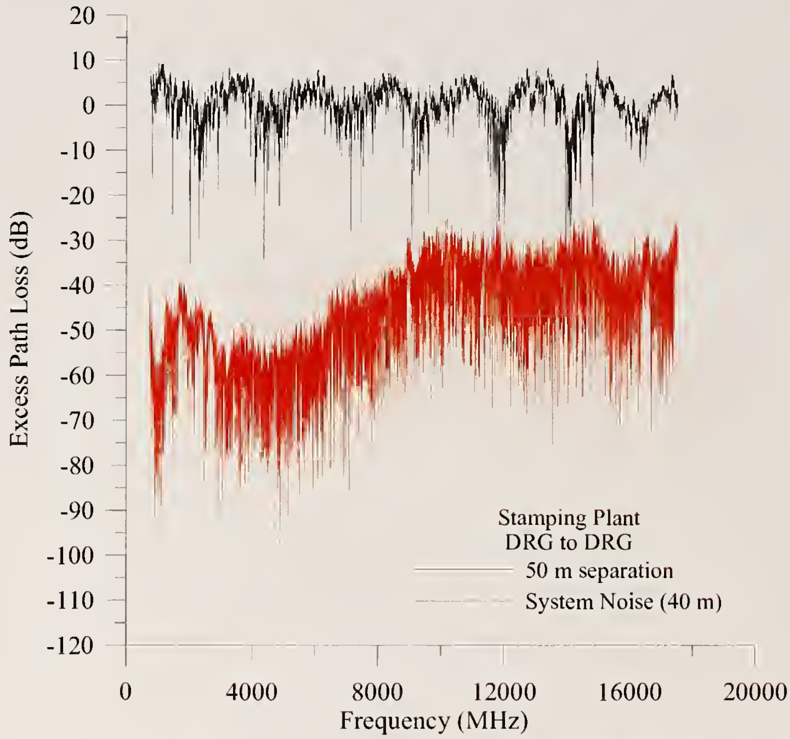


Figure F.2: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 20 m separation. Bottom: 40 m separation.

Stamping Plant: Directional transmit, receive antennas



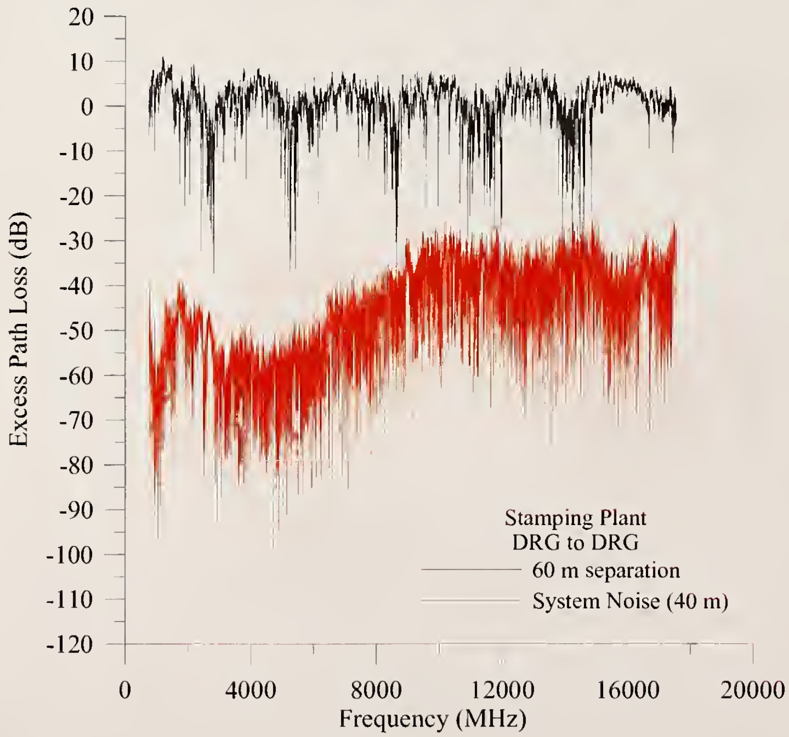
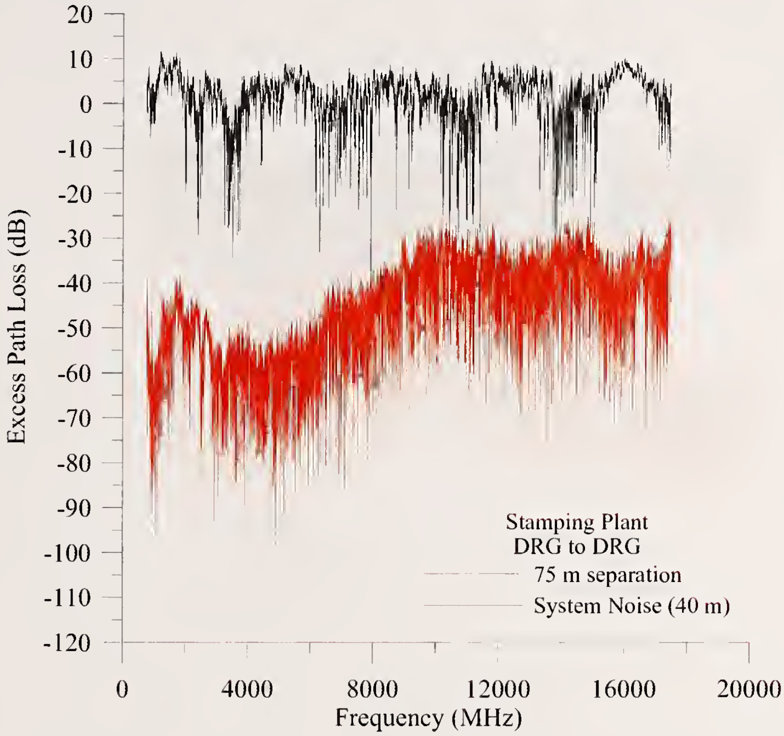


Figure F.3: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 50 m separation. Bottom: 60 m separation.

Stamping Plant: Directional transmit, receive antennas



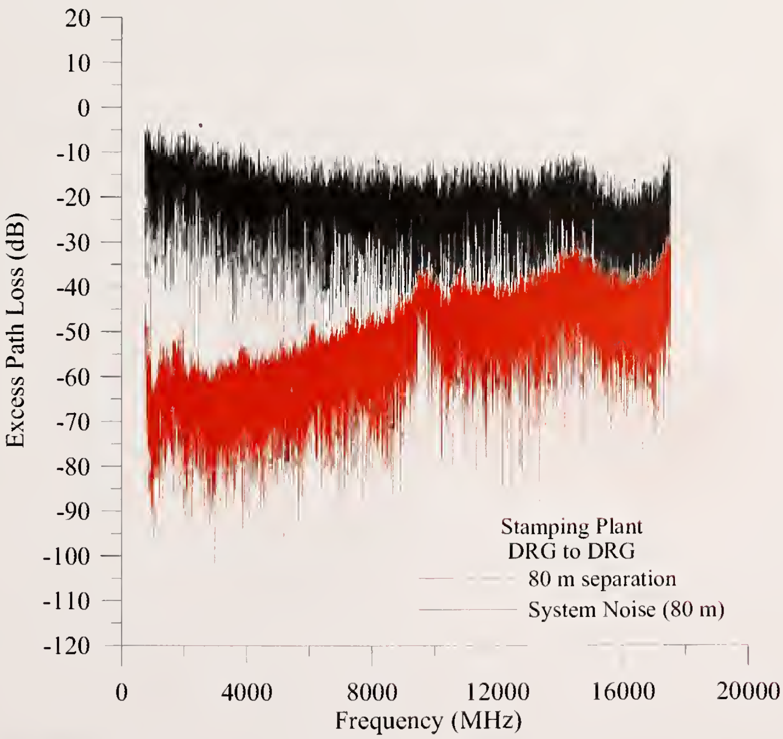
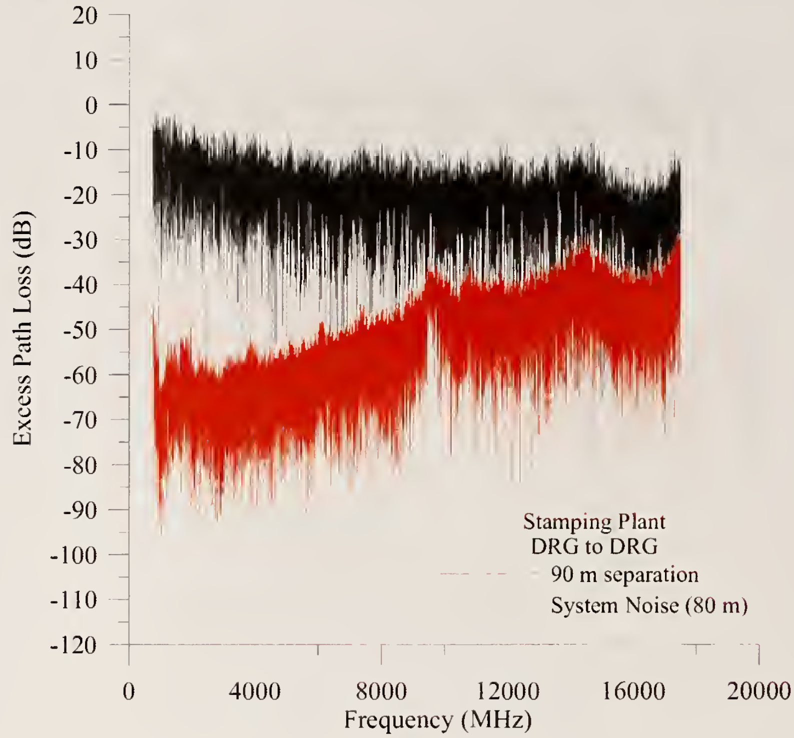


Figure F.4: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 75 m separation. Bottom: 80 m separation.

Stamping Plant: Directional transmit, receive antennas



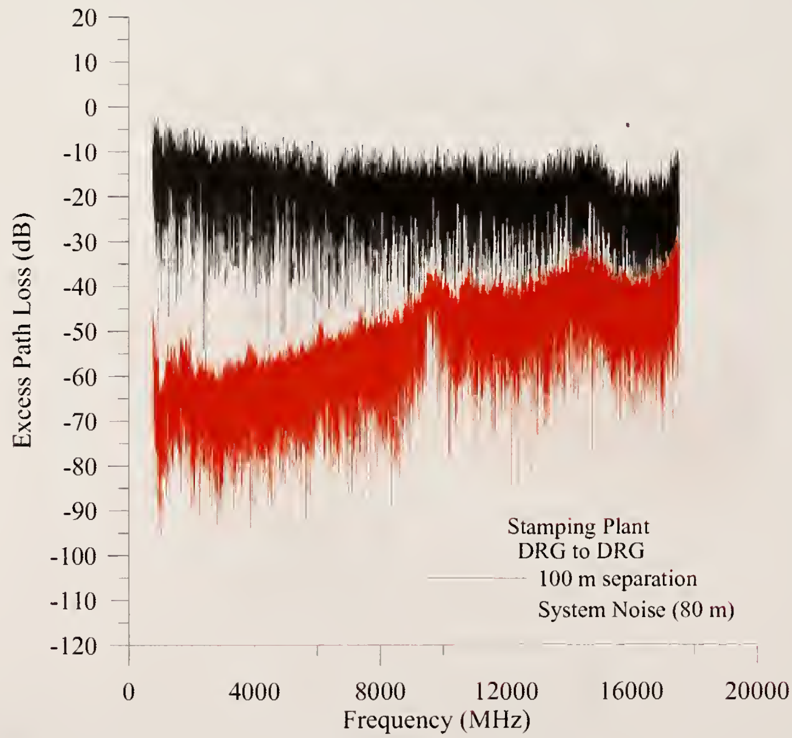
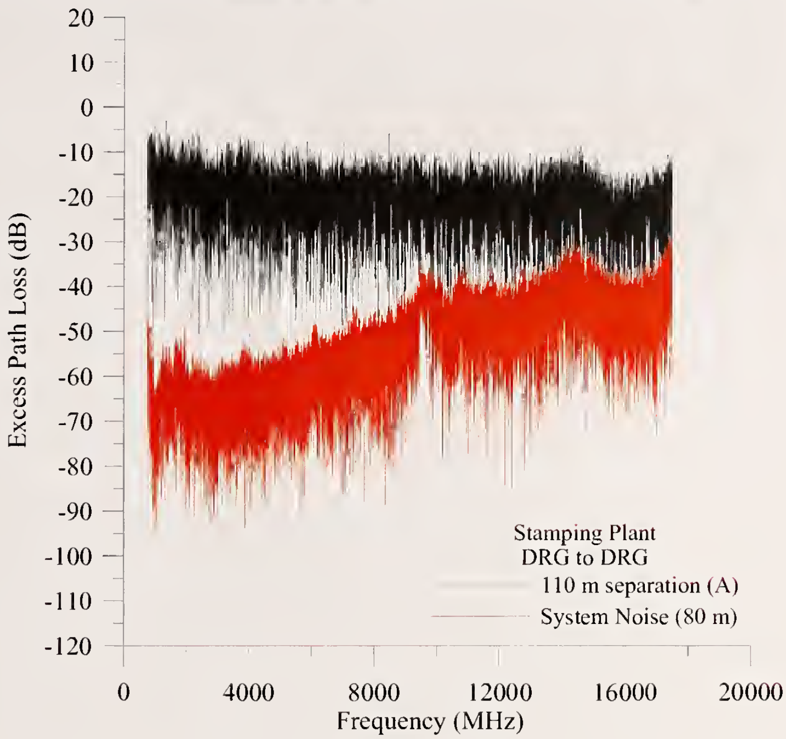


Figure F.5: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 90 m separation. Bottom: 100 m separation.

Stamping Plant: Directional transmit, receive antennas



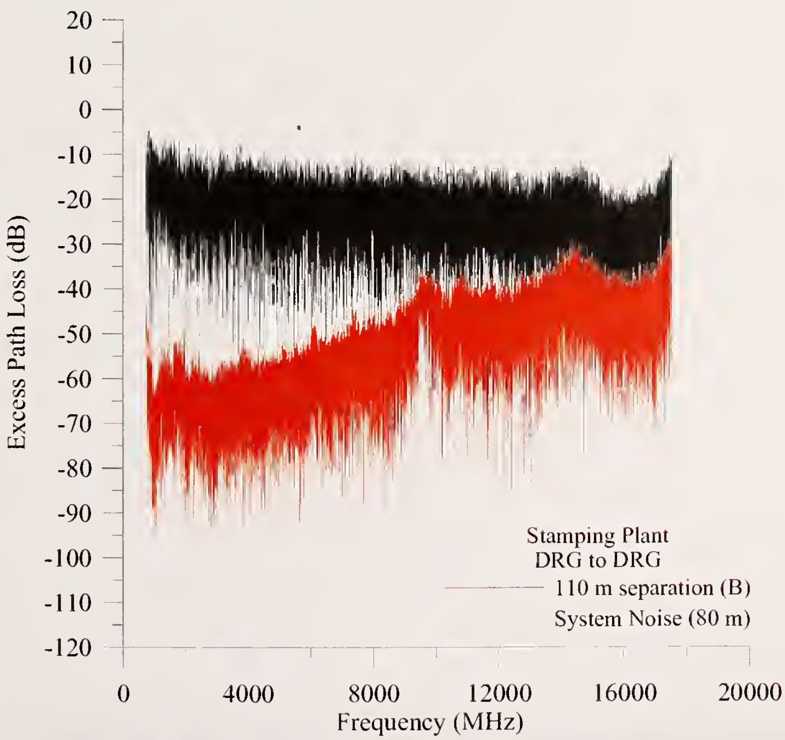


Figure F.6: Excess path loss from 1 GHz to 12 GHz in the stamping plant. Top: 110 m separation, straight. Bottom: 110 m separation, around corner. See Figure 5-3.

Metal Stamping Plant: Directional transmit and receive antennas

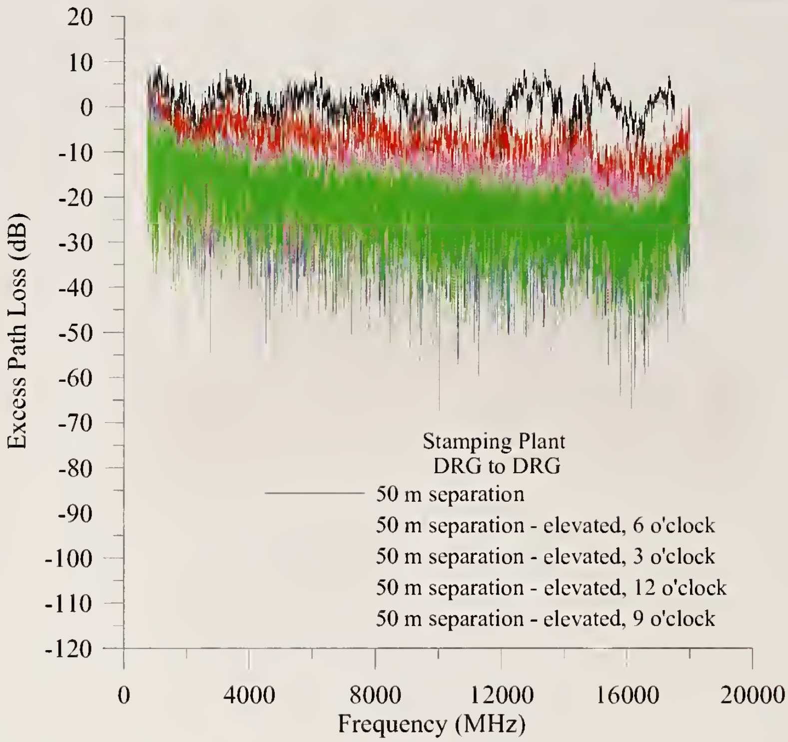
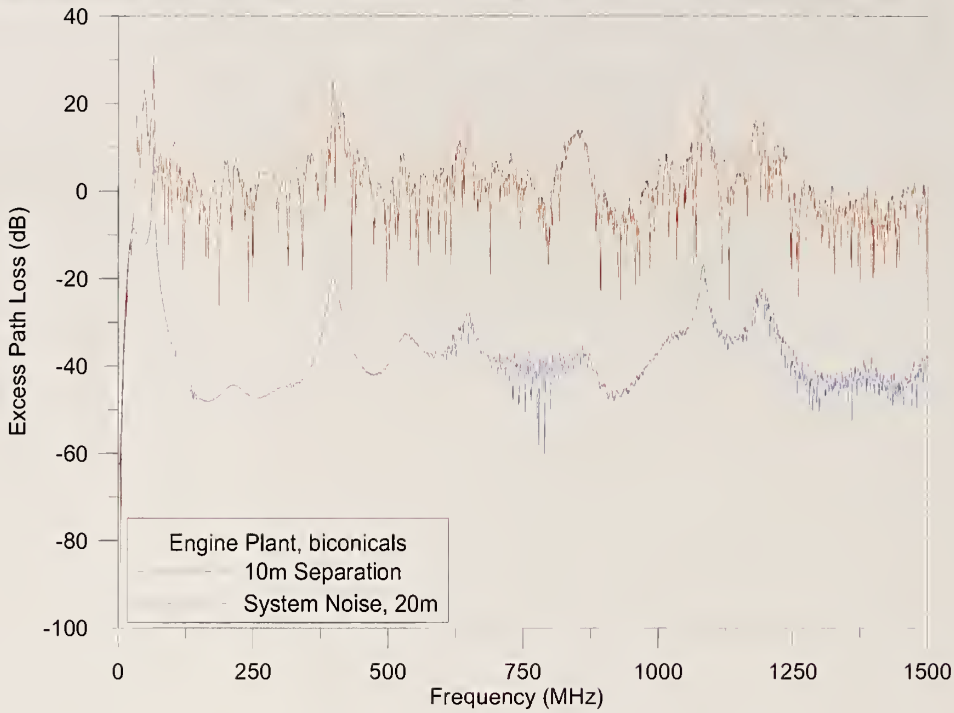


Figure F.7: Excess path loss from 1 GHz to 12 GHz in the metal stamping plant when the receive antenna is rotated through angles from zero (boresight) to 270° as defined in Figure 5-3. Top: 50 m separation.

Appendix G: Engine Plant, Low-Frequency Data, Omnidirectional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the engine plant covering a frequency range of 100 MHz to 1.5 GHz when omnidirectional transmit and receive antennas were used.

Engine Plant: Omnidirectional transmit, receive antennas



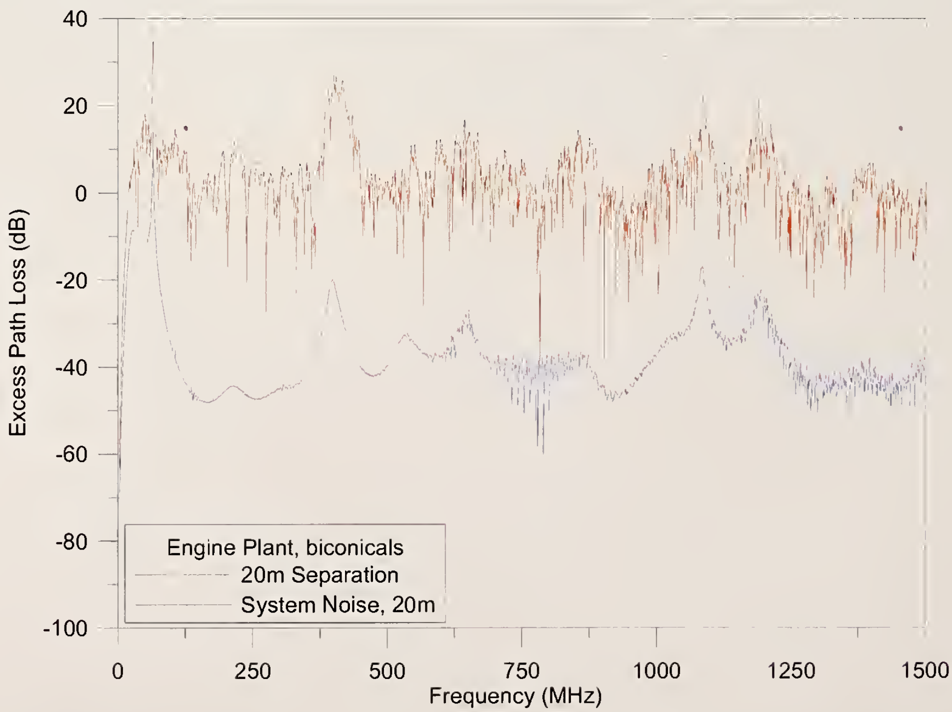


Figure G.1: Excess path loss from 100 MHz to 1.5 GHz in the engine plant. Top: 10 m separation. Bottom: 20 m separation.

Engine Plant: Omnidirectional transmit, receive antennas

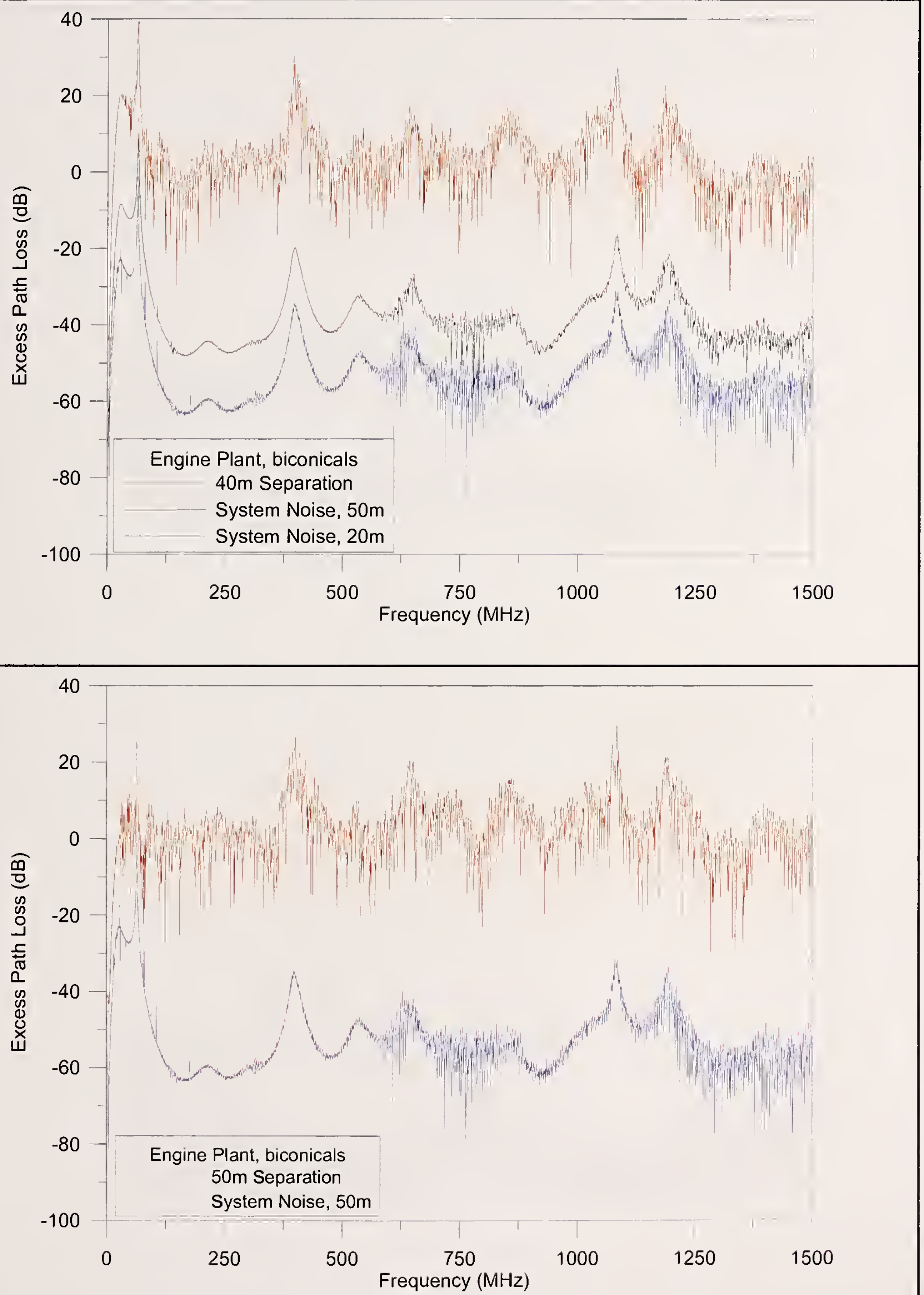


Figure G.2: Excess path loss from 100 MHz to 1.5 GHz in the engine plant. Top: 40 m separation. Bottom: 50 m separation.

Engine Plant: Omnidirectional transmit, receive antennas

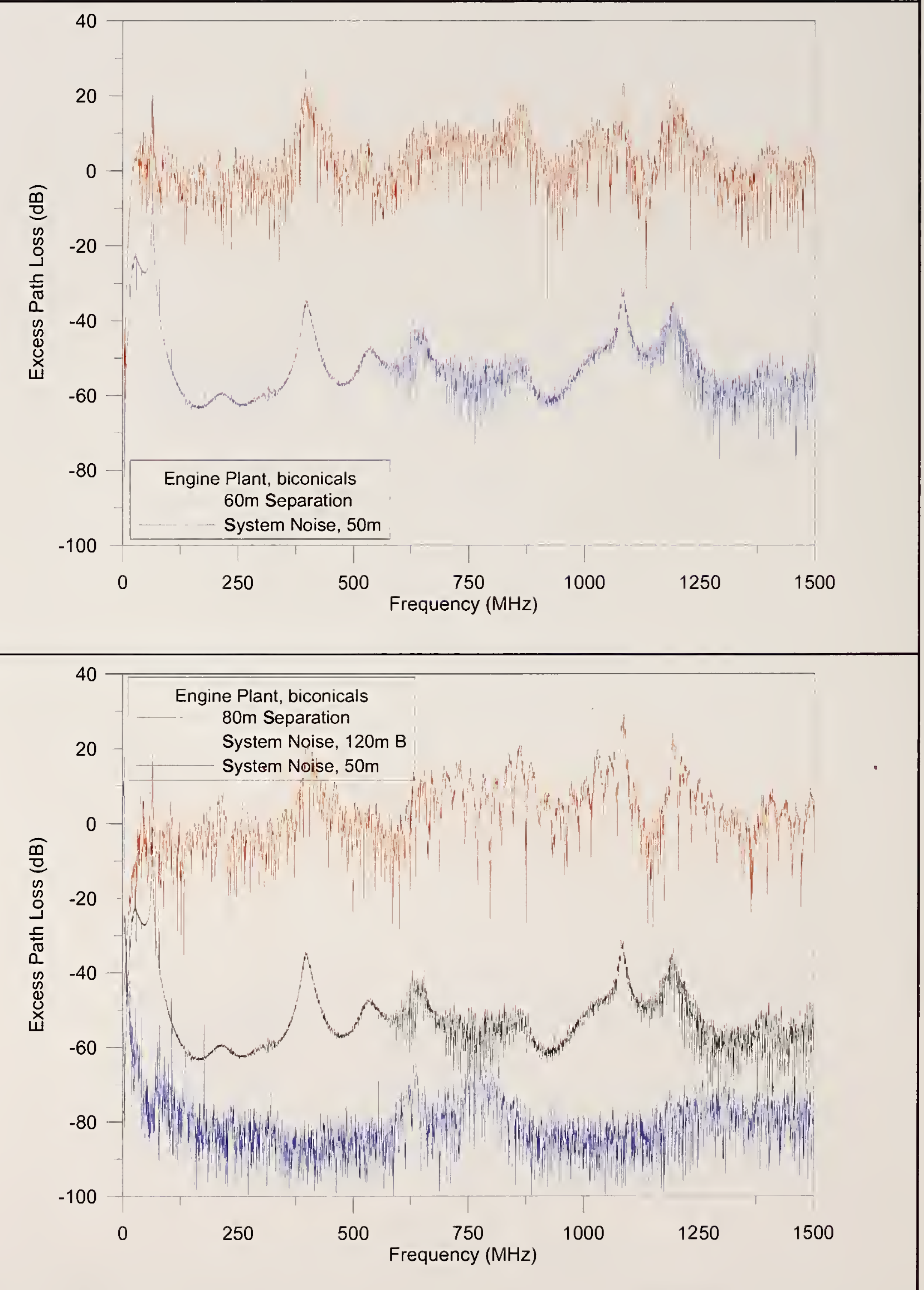
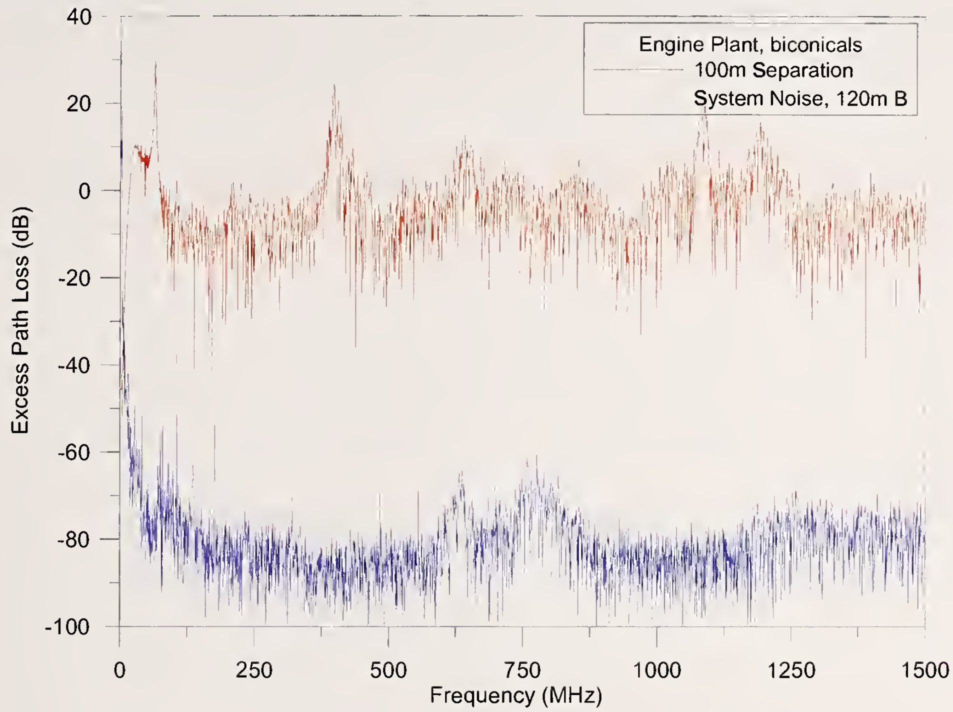


Figure G.3: Excess path loss from 100 MHz to 1.5 GHz in the engine plant. Top: 60 m separation. Bottom: 80 m separation.

Engine Plant: Omnidirectional transmit, receive antennas



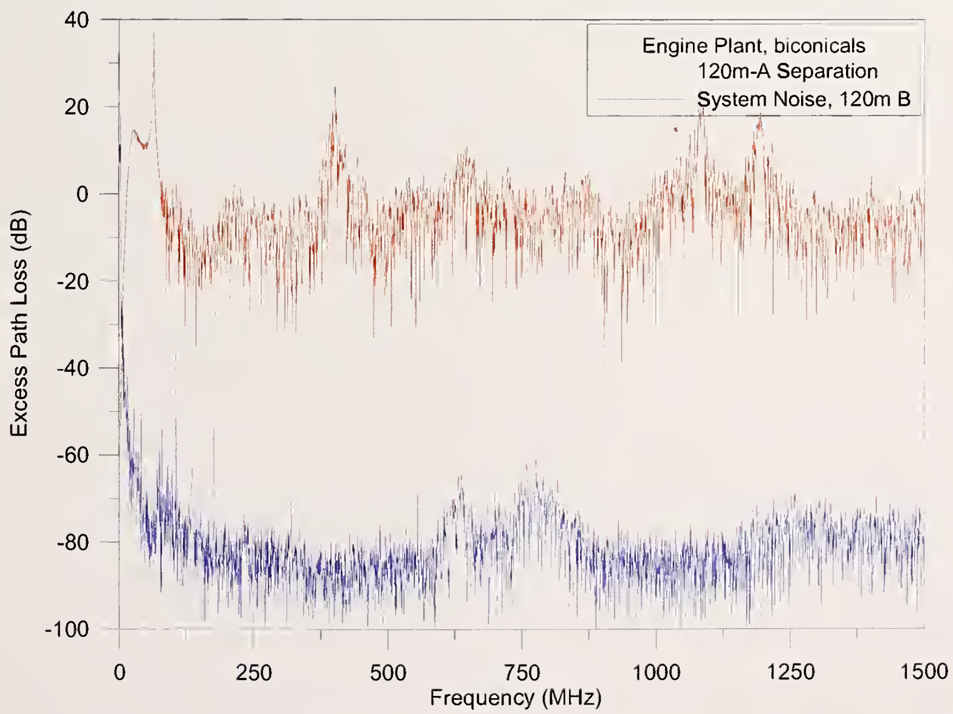


Figure G.4: Excess path loss from 100 MHz to 1.5 GHz in the engine plant. Top: 100 m separation. Bottom: 120 m separation, straight path (see Figure 5-6).

Engine Plant: Omnidirectional transmit, receive antennas

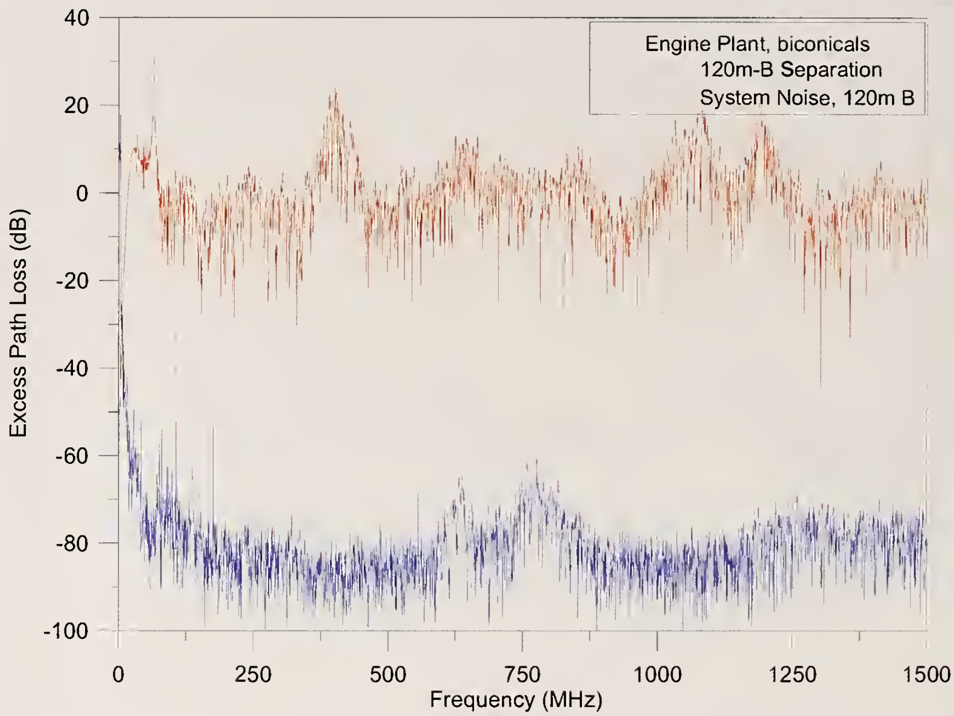


Figure G.5: Excess path loss from 100 MHz to 1.5 GHz in the engine plant. Top: 120 m separation, corner path (see Figure 5-6).

Appendix H: Engine Plant, High-Frequency Data, Directional Transmit Antenna, Omnidirectional Receive Antenna

The following pages contain the complete set of measured data from the engine plant covering a frequency range of 500 MHz to 18 GHz when a directional transmit antenna and an omnidirectional receive antenna were used.

Engine Plant: Directional transmit, omnidirectional receive antennas

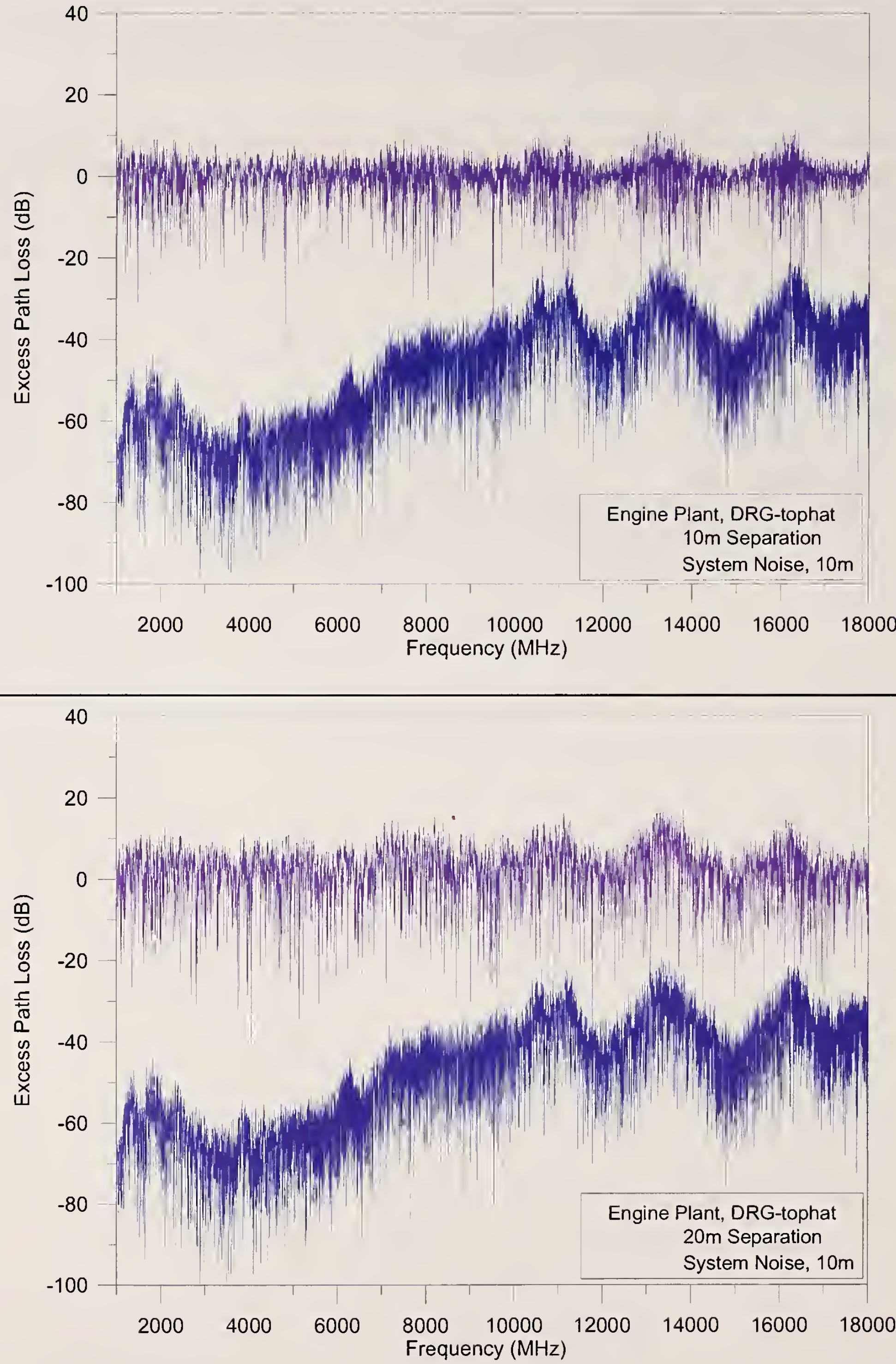
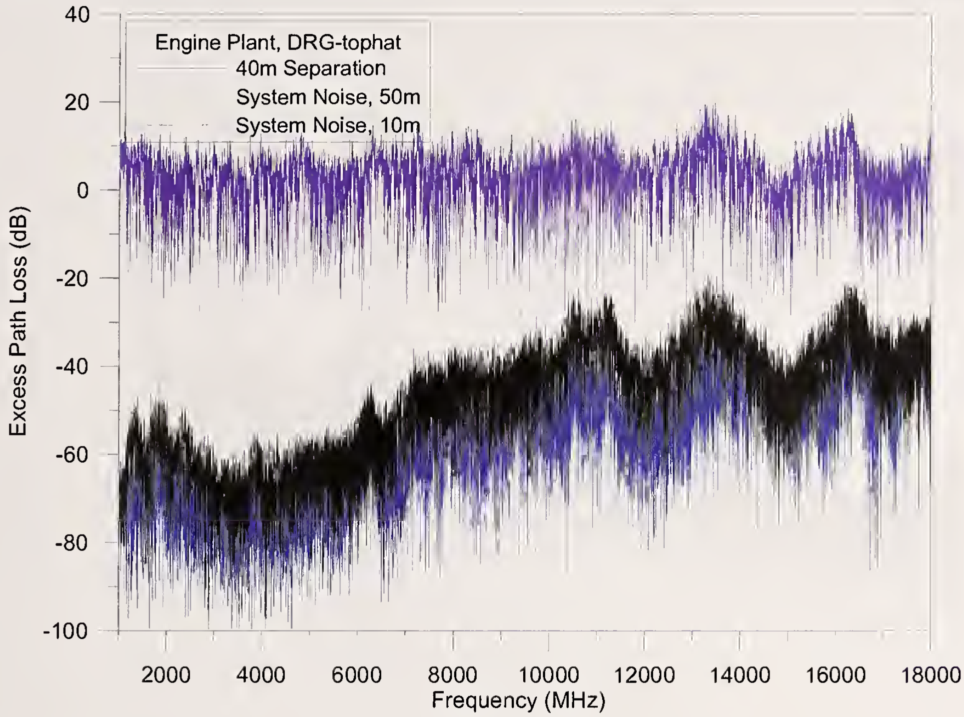


Figure H.1: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 10 m separation. Bottom: 20 m separation.

Engine Plant: Directional transmit, omnidirectional receive antennas



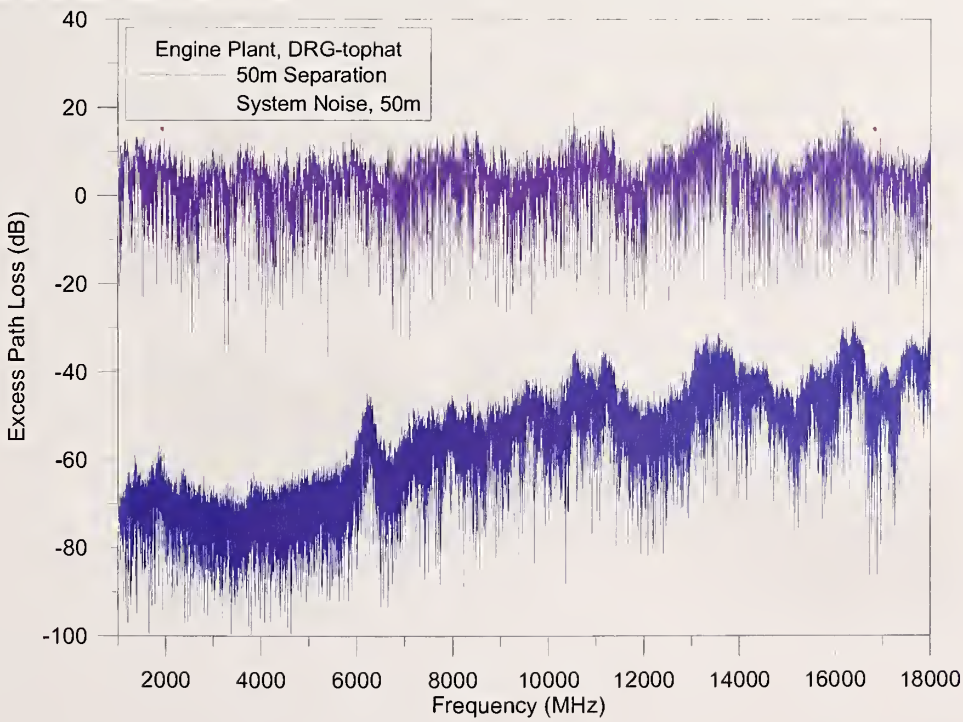
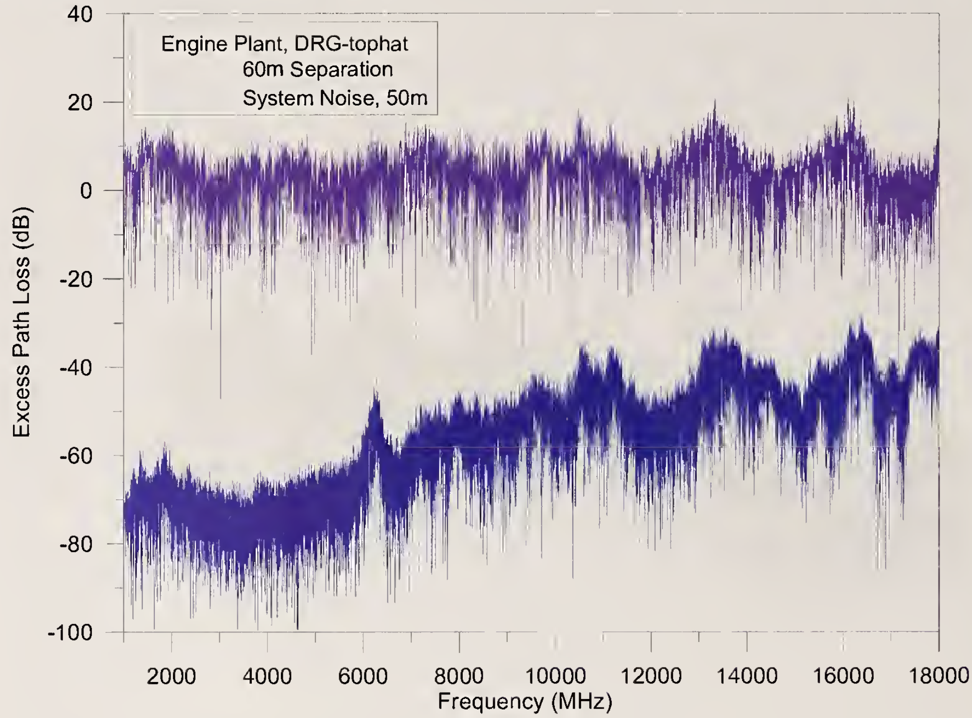


Figure H.2: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 40 m separation. Bottom: 50 m separation.

Engine Plant: Directional transmit, omnidirectional receive antennas



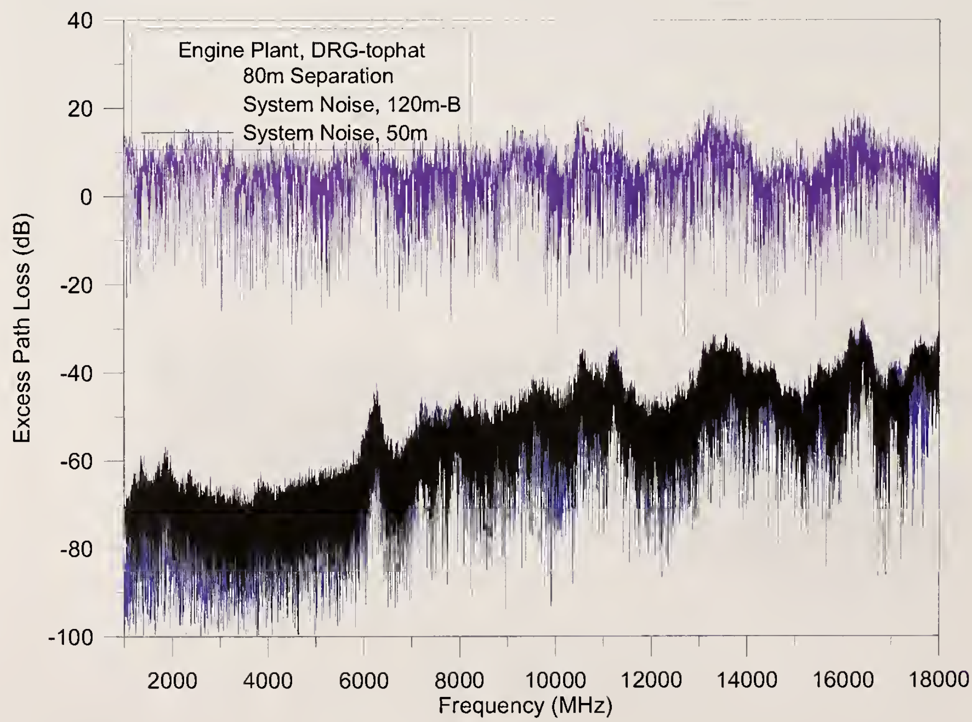
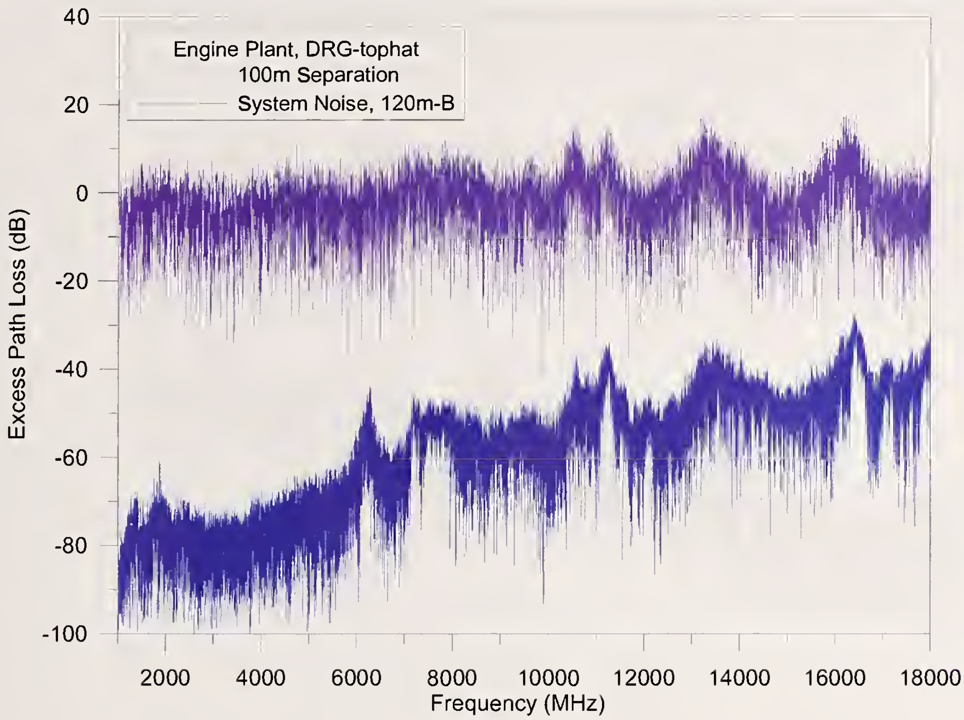


Figure H.3: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 60 m separation. Bottom: 80 m separation.

Engine Plant: Directional transmit, omnidirectional receive antennas



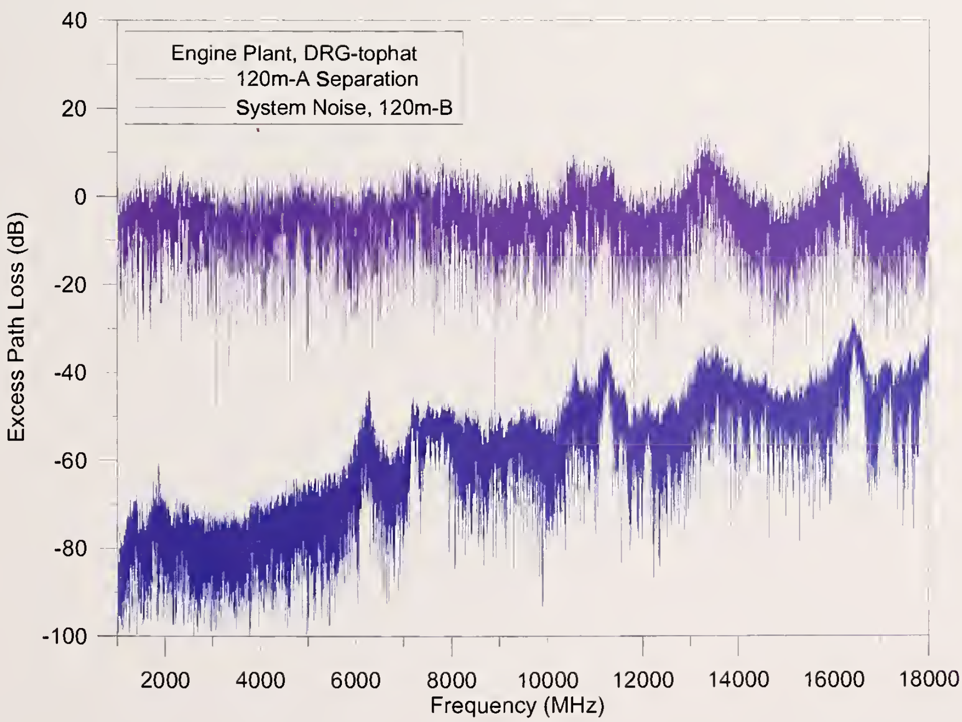


Figure H.4: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 100 m separation. Bottom: 120 m separation, straight path (see Figure 5-6).

Engine Plant: Directional transmit, omnidirectional receive antennas

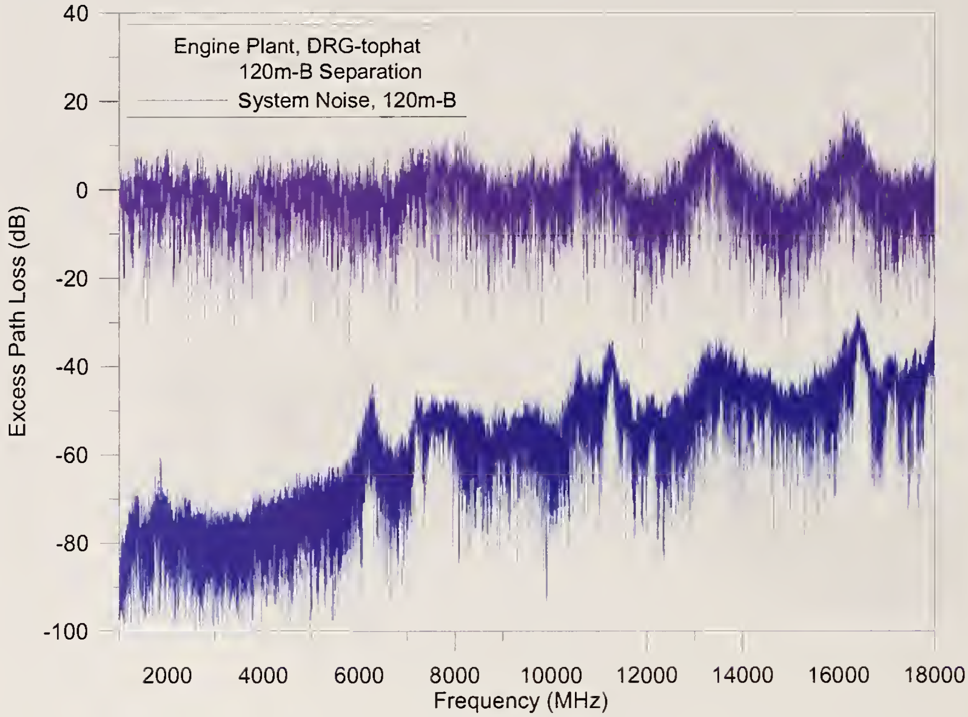
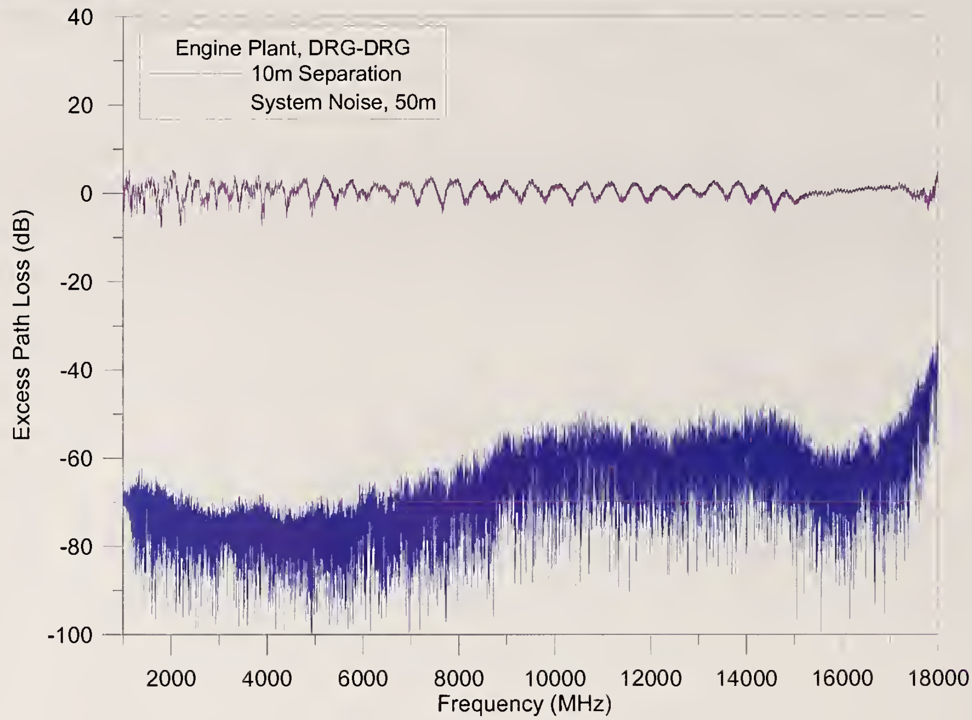


Figure H.5: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 120 m separation, corner path (see Figure 5-6).

Appendix I: Engine Plant, High-Frequency Data, Directional Transmit and Receive Antennas

The following pages contain the complete set of measured data from the engine plant covering a frequency range of 500 MHz to 18 GHz when directional transmit and receive antennas were used.

Engine Plant: Directional transmit, receive antennas



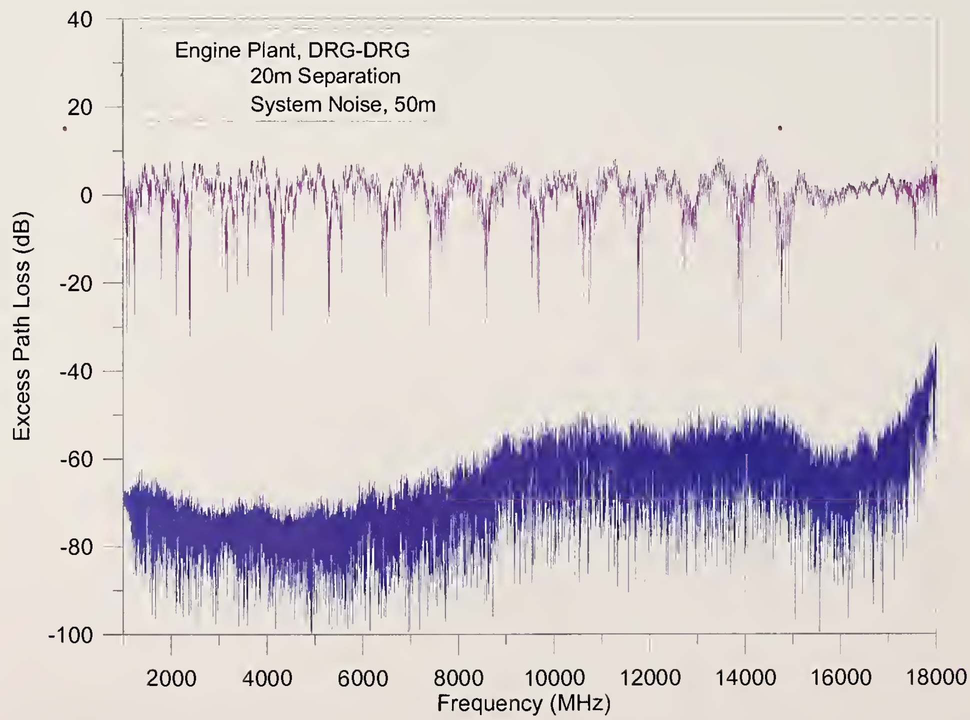


Figure I.1: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 10 m separation. Bottom: 20 m separation.

Engine Plant: Directional transmit, receive antennas

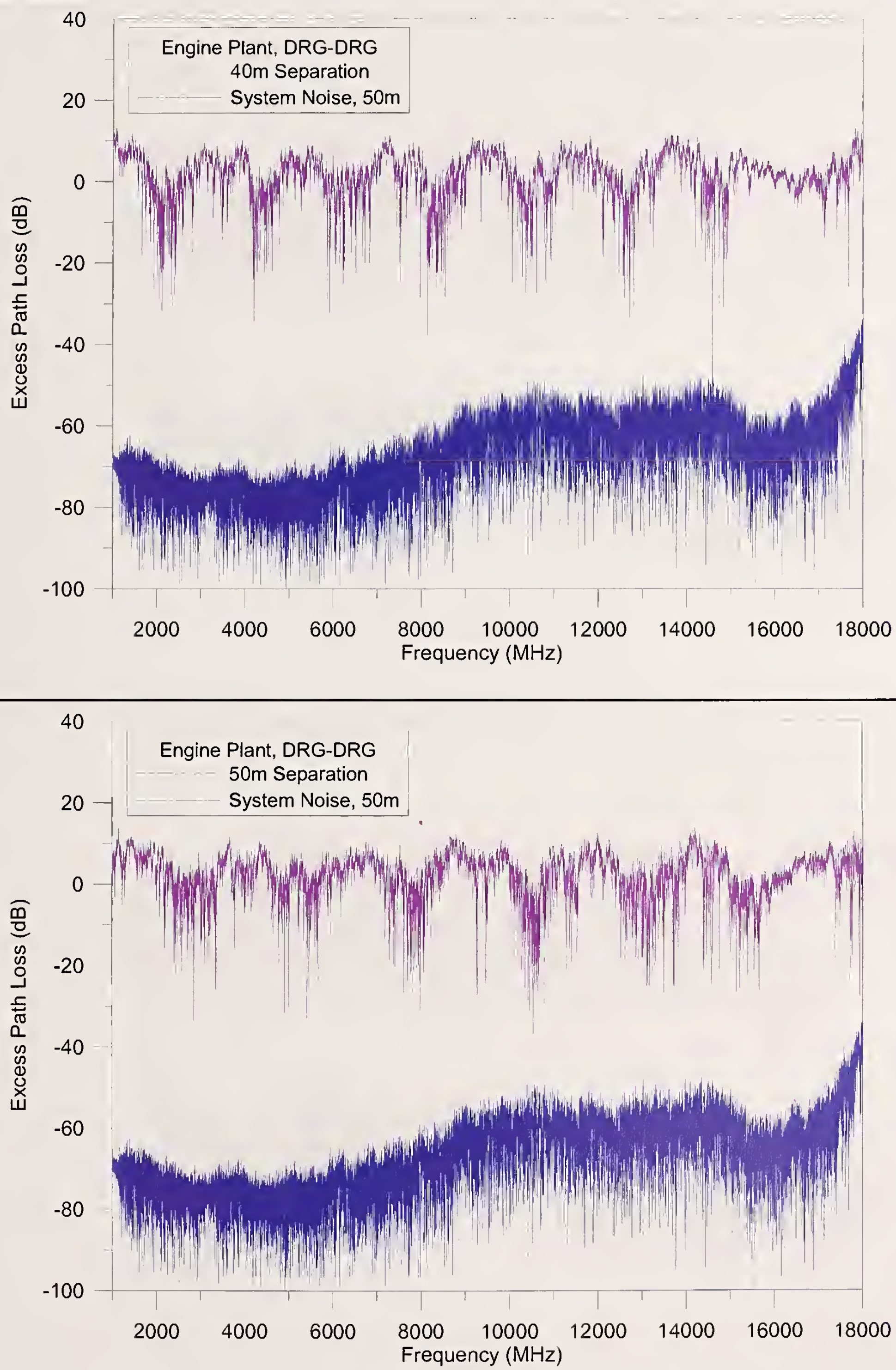
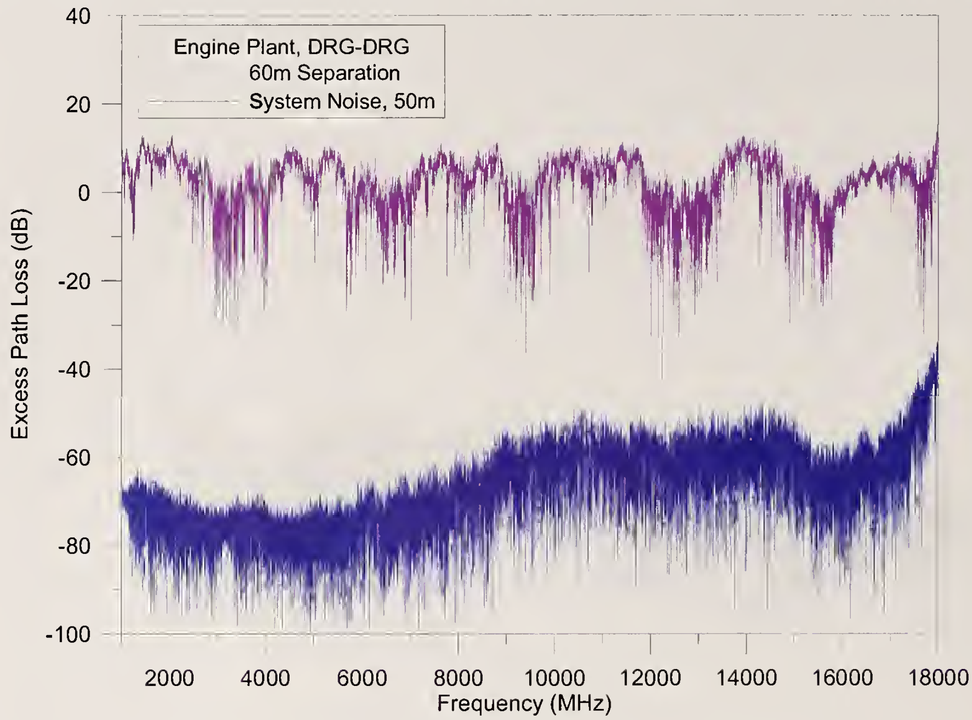


Figure I.2: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 40 m separation. Bottom: 50 m separation.

Engine Plant: Directional transmit, receive antennas



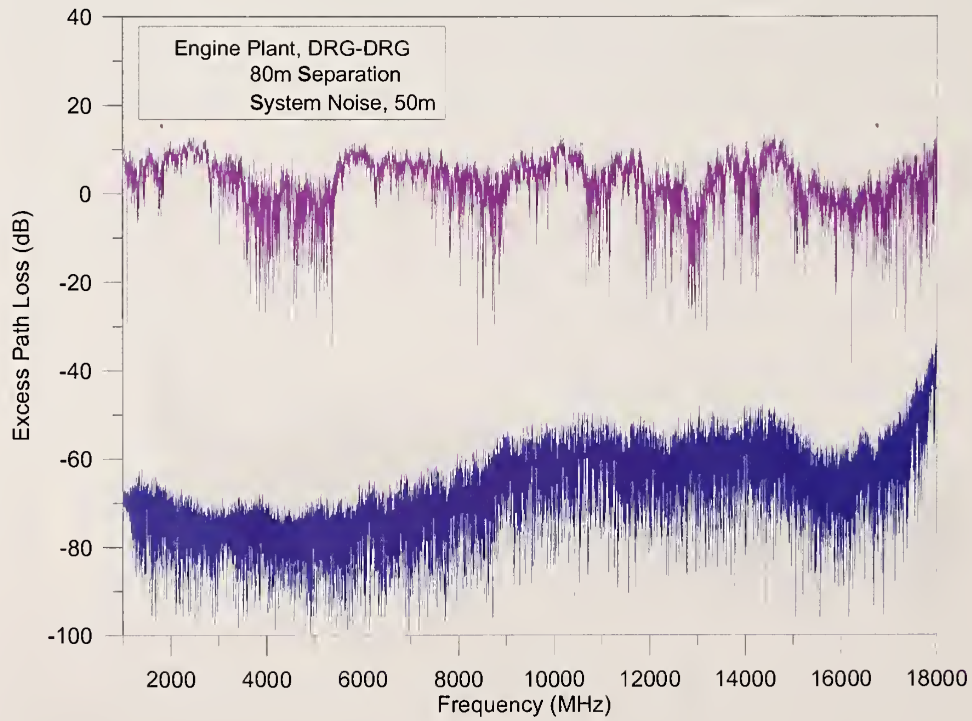
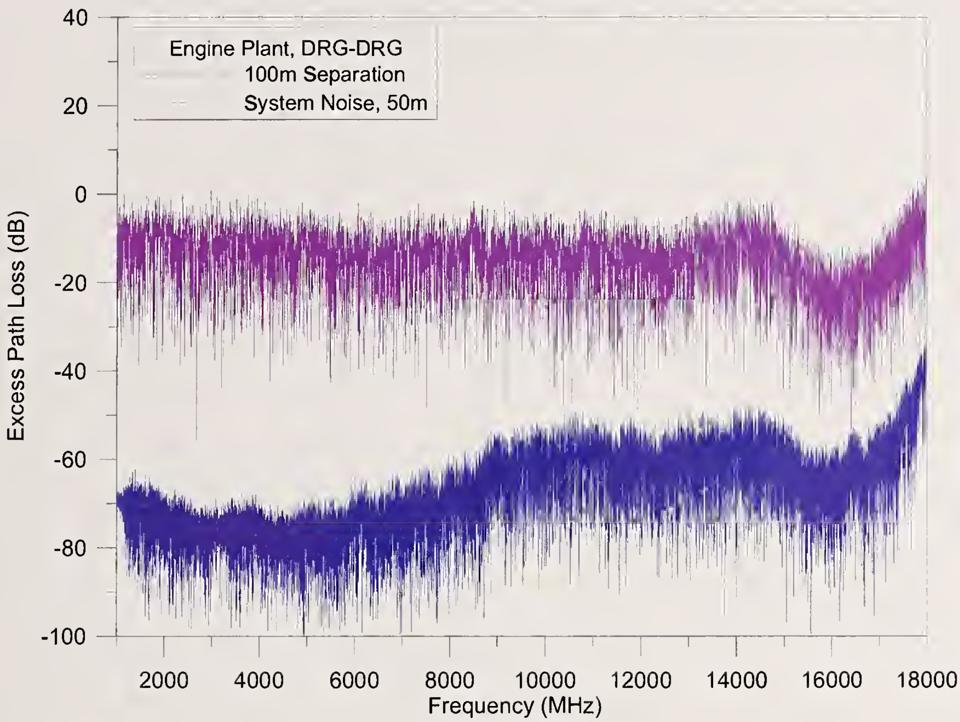


Figure I.3: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 60 m separation. Bottom: 80 m separation.

Engine Plant: Directional transmit, receive antennas



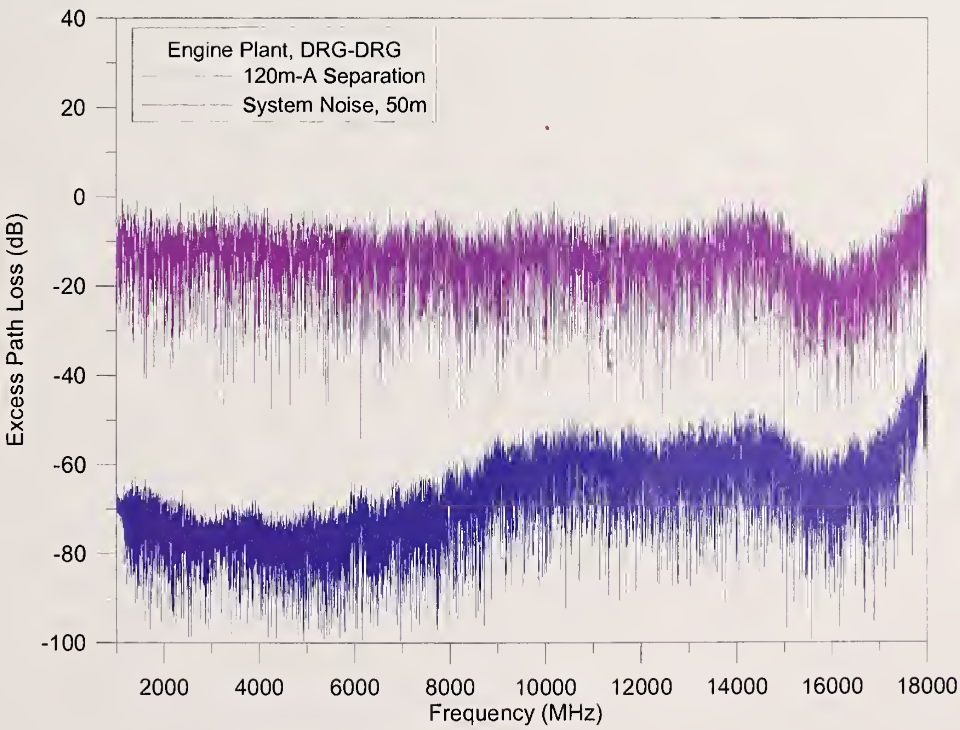


Figure I.4: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top: 100 m separation. Bottom: 120 m separation, straight path (see Figure 5-6).

Engine Plant: Directional transmit, receive antennas

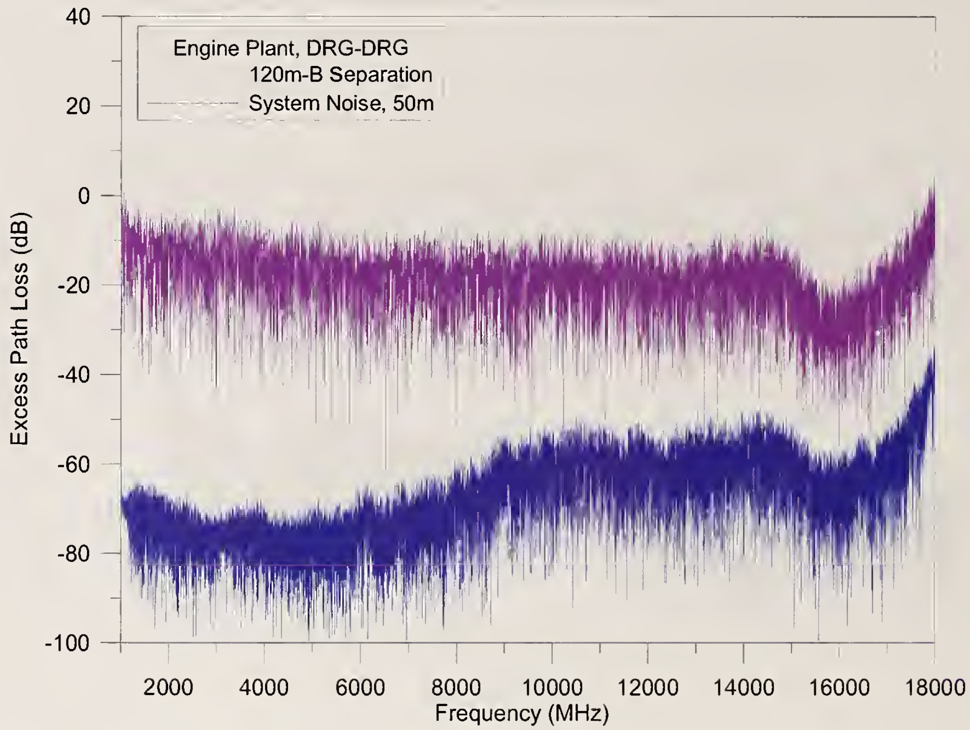


Figure I.5: Excess path loss from 500 MHz to 18 GHz in the engine plant. Top:120 m separation, corner path (see Figure 5-6).

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